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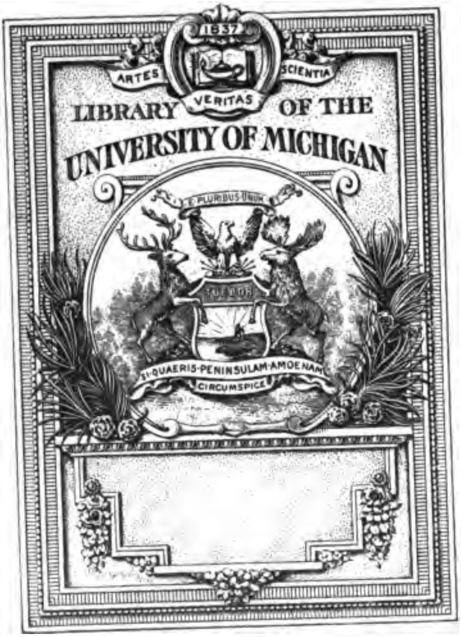
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THE MOVEMENTS OF THE EARTH

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OUTLINES OF PHYSIOGRAPHY

THE
MOVEMENTS OF THE EARTH

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PREFACE.

THE present century is remarkable for the manner in which the unity of Nature, and therefore the unity of Science, which is the study of nature, is being demonstrated to us. We live at a period which, in the coming time, will be looked upon as a very memorable one, because it has taught us that there is as distinct a unity of matter in the universe, as in Newton's time it was clearly demonstrated that there was a unity of force.

The progress of physical science has been in this wise :— As man has grown older the earth on which we dwell has dwindled down. It began as the centre of the universe; it has ended as a small mass of matter revolving round what probably is a small star. But although the progress of science has been thus in a way to degrade the earth, man's intellect has been a distinct gainer by the process; for it is not too much to say that as the earth's place in nature has dwindled down, so has man's mental horizon been extended. In the year 1610, or thereabouts, that is, about two centuries and a half ago, thanks to the labours of men in Holland and in Italy, but chiefly to the genius of the immortal Galileo, the telescope was invented, and we got an untold addition to our mental wealth. The skies were peopled by means of the telescope, and the earth, which up to that time had been supposed the centre of everything, was put in its right place; bodies were observed shining millions and millions of miles away—bodies which up to that time had bathed the earth with light without any response from the human eye; and what was the result? Philosophers were enabled to class all the shining orbs of heaven into two great divisions—those bodies, namely, which shine like the sun with a light of their own, and those which shine by borrowed light. The bodies which were found to shine by borrowed light and not by any light of their own were bodies which eventually were classed together and termed the solar system—a family of planets which go round the sun, each in its proper path, each in its proper time; which are lighted up by the sun; which are warmed by the sun, and to the inhabitants of which the sun is the fountain of every kind of energy. We have from this classification the first great grouping of celestial bodies into those which shine by their own light, which, with the exception of the sun, are outside the solar system; and into those which shine by reflected light, which classification includes all the bodies of the solar system except the sun.

Only a few years ago, when we wished to know anything about matter external to the planet on which we dwell, the only means at our disposal was that furnished us by the fall of those mysterious meteoric masses of iron or stone which are, and were then, found from time to time, some few of which have actually been watched in their fall from the heavens to the earth.

At the present day, however, by means of the spectroscope any particular substance which is known to the chemist here is instantly detected in the most distant regions of the universe, if it happens to be giving out or absorbing light which eventually reaches our eyes.

The result of such observations of distant matter has already been that we find that the matter with which we are familiar in this earth is precisely, either in itself or in its final constituents, that matter which is found in all the regions of space accessible to our inquiries.

Hence these facts have grouped round a new centre. Formerly when we dealt with matter outside our own planet, we were apparently approaching an astronomical subject. This is really not so in the light of modern knowledge, at least in the old sense of the word.

Astronomy may be very sharply divided into two distinct branches: one which I will call mechanical astronomy, which deals with the motions and the exquisite order of the motions of the heavenly bodies; and another, which I will call physical astronomy, which concerns itself not so much with the motions of the masses themselves as with the motions of the molecules of which these masses are built up. In the latter branch we leave the molar forces, that is, those which have to do with the motions of each heavenly body as a whole, and come to the molecular ones, that is, those of the parts of which it is built up. We deal with molecular motion in a star or in a nebula, or in any other cosmical body; but in doing so we follow physical methods which are scarcely yet acclimatised in any observatory. Not only then is the point of view not an astronomical one in the old sense of the word, but it becomes more limited still if celestial kinships are chiefly studied.

What I have set myself to do in this little book and in others which I intend to follow it, is to bring together those lines of thought which will enable us to take a survey of Nature with strict relation to the Earth's Place in it, especially, though not exclusively, from the new standpoint to which I have referred.

We shall have a distinct advantage in beginning with statements regarding the earth, because we live on it; indeed, we shall be adopting the only true way of scientific investigation, namely, gradually travelling outwards from the known. It will also be necessary to pass from the properties of elementary aggregations of matter to those larger aggregations which we call Planet, Sun, Comet, Nebula. In doing this I shall hope to show that I am by no means travelling out of my subject; for what the valley of the Thames is to the whole earth's surface, a molecule of matter is to the whole cosmos.

Facts gleaned concerning the earth will form our stock-in-trade. We shall draw upon mechanical astronomy for those facts which will enable us to form an idea of the earth's place in nature as a member of a system of planets travelling round a star; and then upon the newer astronomy for those others which will furnish us with ideas of its Place in Nature, so far as the past, present, and future of its constituent molecules are concerned. This latter study will enable us to directly compare the earth's present chemical and physical condition with the condition of the other celestial bodies, and to study those interactions of one celestial body on another which are among the most mysterious problems presented to the modern investigator.

The earth has been pretty well studied, and in bringing together the facts concerning it we get a notion of the wonderful interaction and interweaving of all the sciences. It no longer suffices a man to be a geologist, or a chemist, or a biologist; for biology has to lean on chemistry and physics, as they must do on mathematics; the geologist is powerless in the study of his favourite science unless he has a knowledge of physics and chemistry, and so on. If we compare the various sources from which we have derived our present knowledge of the earth, we find that at least four important branches of science, to say the least, have to be drawn upon.

In the first place, the shape and volume and movements of the earth are matters which have been studied by means of geometry. The physics of the earth, by which I mean its present physical condition— such matters as its density and therefore mass; the physical conditions of the materials of which it is composed, apart from their chemical condition —is of course a question for the physicist. Then again the nature of the materials of which the earth is built up, their various compoundings, their various arrangements generally, form a subject with which chemistry alone has to deal. Whilst, last of all—and I say last of all because I am now dealing with the most recent of the sciences — geology comes and tells us of the earth as it existed in past times, and brings to us the idea of successive actions, now of one kind and now of another, which have been and are still going on in this earth of ours.

Now, if we were not to think of the various phenomena presented to us by the matter in all its forms by which we are surrounded until we were profound geometers, or chemists, or physicists, or geologists, we might almost as well be born blind, for they are the very things which strike us most in childhood, side by side with our mother's love. The sky and the cloud, the grass and stones at our feet, the running of the brook, the various forms of animal and vegetable life, each and all fill us with questioning; and for the child there are few blank pages in the book of nature—none which it does not wish to read. Moreover, there is no better discipline for the youthful mind than a careful watching of cause and inevitable effect which are always going on around it. Hence it is that, long before we had any hold on matter beyond our own earth, elementary facts culled from all branches of knowledge, which facts enabled us to comprehend the phenomena continually going on around us, were grouped together to form what has been termed "Physical Geography." Here the earth was the unit. When we pass, as we can now do, however dimly and darkly, from the earth to the universe itself, from γῆ to φύσις, from Geography to Physiography, the extended horizon, while it adds grandeur to the picture, takes away nothing from its orderly beauty or the interest it should possess for mankind.

OUTLINES OF PHYSIOGRAPHY.

THE MOVEMENTS OF THE EARTH

CHAPTER I.

THE MEASUREMENT OF ANGULAR SPACE.

Introductory.

IN dealing with the earth's movements we must first point out how, by means of the application of principles, and methods, and instruments which are generally familiar, and which, at all events, are of daily use, the various movements with which our planet is endowed can be studied. We must do this not only with reference to the phenomena themselves, but with reference also to the causes which lie at the bottom of them.

The various branches of knowledge which will have to be drawn upon in furnishing the materials necessary for this inquiry were really started long before it was imagined that the earth had any movements at all; but still, on the whole, the growth of the knowledge of its movements has been so beautifully continuous, that we cannot do better now than consider historically the way in which those sciences which enable us to make certain measurements have grown up, and to get out correctly certain quantities which must necessarily lie at the bottom of any sound knowledge.

What particular things do we want to measure? It has been already said that when the sciences to which attention will have to be called later on were founded, very few people on this planet knew that it moved at all, but it is now generally known that the earth does move. It will be obvious, however, that whether the earth moves or not (and that we may for a time leave as a moot question), if we wish to form a basis for our judgment in any direction, we must be able to measure time and space. It has been well said that "time and space are the moulds in which phenomena are cast;" for when it is desired to gain any useful knowledge concerning any fact, the relation which it bears to the things around it, and the time of its occurrence must be known; and that is the only thing an astronomer tries to do when he is investigating that portion of his subject to which we must first turn our attention. We will begin, then, by considering those measurements of space which are of the first importance to the astronomer. I do not here refer to the ordinary familiar measurement of inches, yards, and miles, but to the measurement of angles, and it will be well to get a good notion of this angular measurement as soon as possible.

Circles and angles.

There is no special necessity for dividing the circle into 360 parts, but the greatest number of people have made that division, and it is still continued to be done. When the Chinese began to make circles they divided them, not into 360 parts, but into 365¼. Now there was a great advantage, and a great disadvantage about that. The advantage was that this number of divisions in the Chinese circle was the same as the number of days in the year; the disadvantage was that they were not dealing with whole numbers, and their 365¼ was not such a convenient number to halve and quarter, and so on, as is 360. In quite recent times it has been suggested that 400 parts should be taken instead of 360, but that is a suggestion which up to the present time has not been practically acted upon.

We have then an angle defined as the inclination of two straight lines starting from a centre; if we get one of these lines traversing an entire circumference, the other remaining at rest, the travelling line will have traversed 360°; we have what is called a right angle when one of the lines has been separated from the other through a quarter of a circumference—that is 90°. This is the fundamental idea of angular measurement, the only measurement with which we shall have to deal at present.

For instance, if a little ivory rule be opened, its two parts become inclined to each other, and inclose what is known as an angle. That angle may be made large or small by opening and closing the two parts, A and B (see Fig. 1) of the rule. Suppose that, whilst A remains at rest, B is made to travel successively through B and B^1 to B^2, the point on which it turns being in the centre of the circle, C D E F. It will then have travelled half the circumference of the circle C D E F, but civilised people, in order to get perfectly clear notions about this measurement, and to be able to tell each other what particular measurement they have made in this way, instead of talking of a circumference merely, and of certain rough divisions of it, have divided all circles into 360 parts called degrees, and say that the travelling part, B, of the rule has travelled through not a quarter, or a half circumference, but through 90 and 180 degrees respectively.

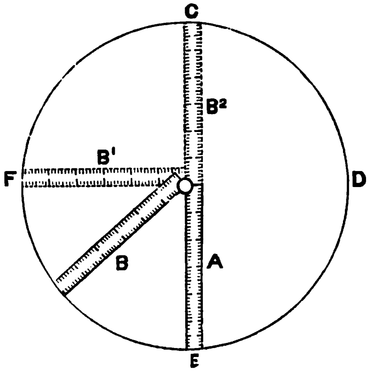

FIG. 1.—Use of a two-foot rule to explain angular measurement. With the part A at rest, the movement of the other to B, B1 and B2 gives us 45°, 90°, and 180°.

The use of angular measurement.

Why are these measurements of space required? For the reason that when we are dealing with the heavenly bodies and seeking to define the position of any object, two facts at least are required to be known before its exact position can be determined. An observer going out at night upon an extended plain would see some celestial bodies near where the earth meets the sky all round, which is called the circle of the horizon, and he might happen to see another body exactly overhead, in what is called the zenith. In passing from this zenith to the horizon, it will be obvious that a quarter of a circumference is traversed (see Fig. 2). That distance may therefore be divided into 90°. Similarly in passing from the eastern horizon to the western horizon, half a circumference is travelled over. This distance, therefore, is divided into 180° of angular measurement in the same way that the half of the circumference traversed by the travelling rule was divided into 180°.

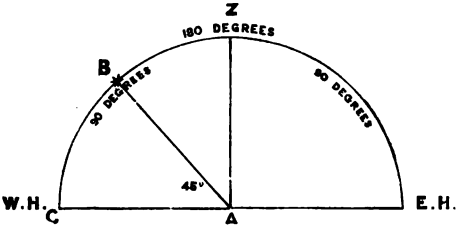

FIG. 2.—Measurement of altitudes.

Now if it can be ascertained of any body that it is exactly in the zenith, the position of that one body has been definitely stated for the particular time at which the observation is made. But consider the case of another body not in the zenith. Suppose that the lines, the one A B (see Fig. 2), passing from the observer to the object, and the other, A C, passing from the observer to the horizon, inclose an angle of 45°. This angle is called the star's altitude. But to say simply that the altitude of a star is 45° does not sufficiently define its position. Let the reader imagine himself to be standing in the centre of the Albert Hall. He knows that he may look up and see rows of panes of glass and ornamented work running around the hall at different heights. He may also notice, let us say, various series of ornamentation arranged vertically from floor to roof. Now suppose it were desired to define the position of any one pane of glass or piece of ornamentation in any one of these horizontal or vertical rows. It is obvious that to say of any pane of glass at one level that it is at a certain height above the floor will not suffice, for all the panes of glass in that row are at the same elevation. In like manner, in defining the position of any one piece of ornamentation in the vertical series, it will not be sufficient to say that it is at a certain angular distance from any one point, say a door; because all the pieces in the same row are at this angular distance from the door. But if these two methods of stating position be combined, if the height above the ground as well as the angular distance from the door be given, then a definite statement may be made both of the position of the pane of glass and of the piece of ornamentation.

Altitude and azimuth.

Let us now pass to the stars. Imagine a horizontal circle passing from north to south, and thence to north again. A line from the zenith through any body will cut this circle at some one point, and the number of degrees included between that point and the north point will give the angular distance from the north point, or, as it is called, the azimuth. The whole of an imaginary line of bodies extending from the zenith to the horizon will have the same azimuth (see Fig. 3). In the same way we may imagine a whole ring of bodies at the same height above the horizon, having the same altitude (see Fig. 3), but a particular altitude and a particular azimuth can be true of only one of those bodies. It is in this way, then, by a statement of the altitude and azimuth, that the position of a star or other celestial body can be indicated with reference to any one particular place of observation and any one particular instant of time.

It is by thus dealing with this angular measurement that the exact positions of the heavenly bodies have been determined. This point has been discussed at some length, because in making an historical survey it will be found, that the growth of that particular knowledge of which we shall come to speak, has been the growth of man's capability of getting finer and finer in this angular measurement.

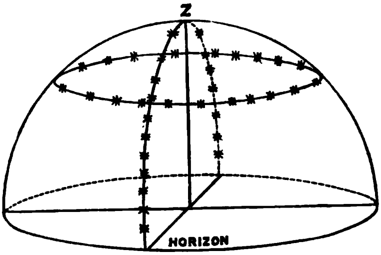

FIG. 3.—Stars with equal altitudes and stars with equal azimuths.

To go back to the time of the Greeks, Hipparchus, one of the most eminent of ancient observers, could even in his day define the position of a heavenly body to within one-third of a degree. Since these 360 degrees into which circles are divided are each subdivided, first into sixty minutes, and each of these again into sixty seconds, the one-third of a degree to which Hipparchus attained may be called twenty minutes of arc. Passing from his time to the middle ages, a most interesting instrument then in use claims attention. Fig. 4 is a copy of a photograph of it.

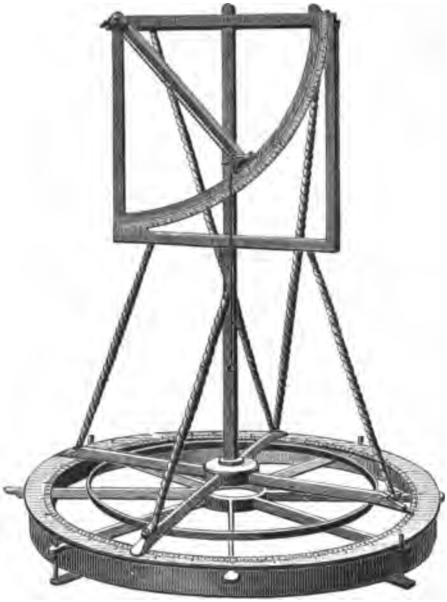

FIG. 4.—Tycho Brahe's altitude and azimuth instrument.

The model, from which the photograph has been taken, is an exact copy of an instrument made by one of the most industrious astronomers that ever lived, Tycho Brahe, and shows how, even in the very beginning of this observational science, men got at a very admirable way of making their observations, considering the means they had at their disposal.

Tycho Brahe's instrument.

First there was in this instrument a quadrant of a circle (see Fig. 4), which served its purpose just as well as a whole circle. Combined with this was an arrangement somewhat resembling the "sights" on a modern rifle. Remember this was before the days of telescopes. So they started with these sights and a little pinhole, that they might take a shot, as it were, at a heavenly body, putting the eye near the pinhole, and seeing the heavenly body in a line with the front sight. Then the instrument was provided with a plumb-line to show the vertical. This plumb-line was so arranged that when the sight lay along it, a body in the zenith would be observed, and an angle of 90° altitude recorded. With the instrument thus set, any smaller altitude could be read along the quadrant, according to the position of the line of sight passing through the eye, the centre of the quadrant, and the place of the heavenly body.

To obtain azimuth, a horizontal circle, shown at the base, also divided into degrees and provided with a pointer, was added. By sweeping the instrument round until the azimuth was such that the body was seen through the pinhole, and the altitude was such that it was seen in a line with the front sight, they fixed its position, as well as that instrument enabled it to be done. Supposing that their circles were properly divided, it was quite easy to determine a division as small as the quarter of a degree. This would put Tycho Brahe in only a little better position than Hipparchus. That is to say, from the time of the Greeks until about the end of the sixteenth century, the only advance made with this angular measurement, was that a reading of one-third was improved into a reading of one-fourth of a degree.

Improved methods of pointing.

Another notable improvement and advance towards a finer and more accurate measurement was made by Digges.

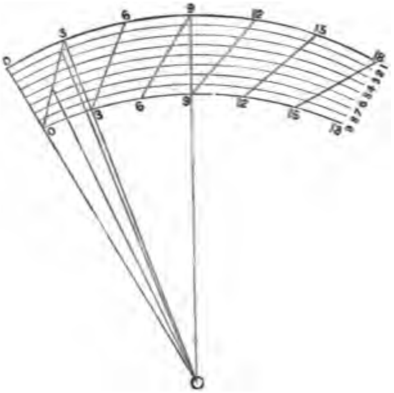

FIG 5.—Digges' diagonal scale.

He introduced the diagonal scale, the principle of which is shown in Fig. 5. The arrangement consists of a number of concentric circles, in this case nine, drawn at equal distances apart. The distance between the divisions of the inner and outer circles is 3°, both starting from the same radial line. From each of the divisions on the inner circle, diagonal lines are drawn to the outer circle in such a manner that the diagonal cutting the first circle at 0° cuts the ninth circle at 3°. That cutting the first circle at 3° cuts the outer circle at 6°. So with the other diagonal lines. Consider the diagonal passing from 0° on the inner circle to 3° on the outer. If the pointer cuts the diagonal at the former point, an observation of 0° will have been made; if it cuts at the latter point, an observation of 3° will have been made. But it may cut the scale at some intermediate point. Suppose it falls where the eighth of the nine concentric circles meets the diagonal, then the value of the observation will be 7/8ths of 3° (eighths because there are only eight spaces between the circles). Should the pointer fall half way between 0° and 3°, that is on the fifth circle, the reading will be 4/8ths of 3°. So with the other intermediate points. For finer readings, the first divisions are smaller, and a greater number of circles are drawn. In this way, then, Digges enabled a much greater accuracy to be attained in this circle reading.

The next great improvement after that of Digges was one made by Vernier, a Frenchman, who, in about the year 1631, invented the instrument which bears his name. The following is the arrangement. Let the scale on which the measurements are made be divided into a certain number of parts. Take a second scale called the vernier, shorter than the first by the length of one of its divisions, and make the number of divisions in this vernier equal to the number of divisions in the scale. Then each of the divisions of the vernier will be less than each of the parts of the scale, by a fraction having one for its numerator, and the number of divisions in the scale or vernier respectively for its denominator. Thus if the number of divisions be ten (see Fig. 6), and the vernier equal in length to nine of such parts has also ten divisions, each of these divisions will be shorter by 1/10th than each of the parts of the scale. If the number of divisions be seventeen (see Fig. 8), the different parts of the vernier will be less by 1/17th than each of the divisions of the scale. So when the number of divisions is thirty (see Fig. 9), the parts of the vernier will be less by 1/30th

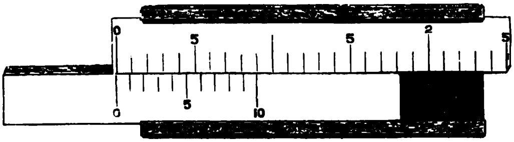

FIG. 6.—Vernier reading to tenths of divisions.

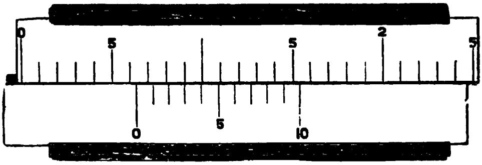

FIG. 7.—Vernier shown in Fig. 6 reading to 6 and $\frac{3}{10}$.

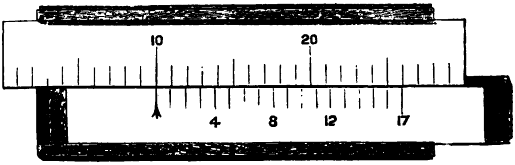

FIG. 8.—Vernier reading to seventeenths.

than the divisions of the scale. The arrangement, however, is not limited to straight scales. It may also be used for the determination of small fractions of degrees on a circle.

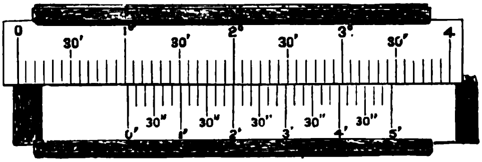

Fig. 9.—Application of vernier to a circle reading to ten seconds of arc.

Fig. 10 represents a vernier giving tenths of degrees on a circle. It need hardly be said that the vernier may be constructed to give readings upon the inner as well as the outer edge of the graduation.

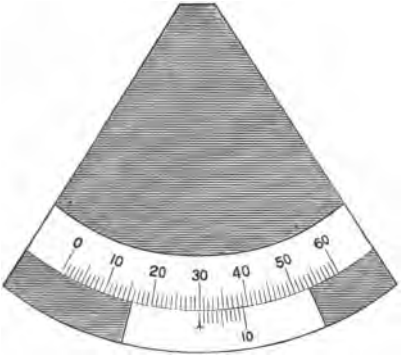

Fig. 10.—Application of vernier to circle reading to one-tenth of a degree.

In using the vernier the observer looks along it until he finds a coincidence, that is for a point where one of the divisions on the scale coincides with a division on the vernier. If this occurs at the eighth division, say, the observation is some whole number, and 8/10ths, 8/17ths, or 8/30ths, according as the scale used is divided into ten, seventeen, or thirty parts. In Fig. 7 the coincidence occurs at the third division; the reading in that case would be some whole number and 3/10ths.

To the instrument of Tycho Brahe, then, the vernier, which can be adapted to it, has now been added. Of course by taking divisions enough the measurement may be made as fine as possible. A vernier of 100 divisions may replace the vernier of 10, of 17, or of 30 divisions. Seventeen divisions have been chosen to show that the principle is not limited to tenths; any number of divisions may be taken. A very fine degree of accuracy can be attained then in angular measurement, owing to the introduction of the vernier, and that is why there is what is practically a vernier upon almost every measuring instrument in every workshop and laboratory. The question next arises whether with the introduction of the vernier the limit of accuracy has been reached, or whether it be possible to go beyond this. A negative reply may be made to the first part of this question. The limit of accuracy has not here been reached. In order to get more accuracy in this angular measurement, it is only necessary to add some branch of physical science to those geometrical considerations by means of which circles have been so finely divided. The astronomer culls certain portions out of the science of optics, and uses them for his purpose. It is perfectly clear that the reason a limit is reached with an arrangement of the nature of the vernier is, that at last the divisions get so small that the eye cannot distinguish them, so that optical principles have to be appealed to to increase the power of the eye.

Introduction of optical principles.

Before discussing this question of whether it be possible to select some principle of optics, by the application of which the power of the eye may be increased, it will be well to consider briefly in what that power consists. Fig. 11 will give a rough notion of those parts of the eye which specially relate to this matter. Why we see at all will be discussed in a subsequent chapter. First comes the curved surface *Cn*, the cornea, and next *Aq*, the small anterior chamber which contains the aqueous humour. Behind this comes *Ir*, the iris, which limits the amount of light entering the eye, this being immediately succeeded by *Cry*, the crystalline lens. Then comes the large posterior chamber

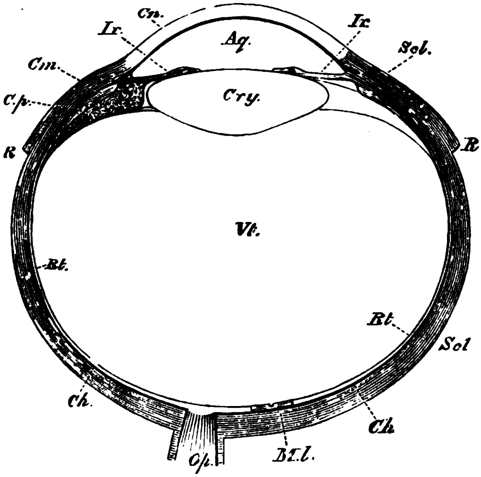

FIG. 11.—Horizontal section of the human eye.

of the eye which contains the vitreous humour. Behind this the optic nerve enters the eyeball, expanding itself into the delicate layer of nervous elements, *Rt*, which lines the inner surface of the vitreous cavity.

When any object is seen by the eye, the rays of light emanating from that object, impinge first upon the curved corneal surface, and have to pass successively through *Aq*, *Cry*, and *Vt*, before they can affect the nervous retinal elements and cause the sensation of sight. In passing through these portions of the eye, the rays of light are dealt with in a peculiar manner, especially perhaps by the crystalline lens, and are brought together, to form what is called an image, on the retina. This image influences the nervous elements of which the retina is composed in such a way, that a sort of telegram is sent to the brain through the optic nerve, and the brain becomes conscious of having seen something; the particular object seen being included in the message. Another diagram (Fig. 12) will perhaps make it a little clearer how this image on the retina is formed. At *A B* is an arrow; from it rays of light are marked going to two different points on the retina. But it will be seen that those rays of light which come from the top of the arrow are, by the action of these three media, deviated, and form an image of the top portion of the arrow on a low part of the retina. The rays of light proceeding from the bottom of the arrow are deviated, so that its image is formed on an upper part of the retina. The light coming from the middle of the arrow is less deviated, and therefore forms its image on a middle portion of the retina. That is the way in which the eye deals with rays of light entering it. With this knowledge of the optics of the eye, it will be very easily seen how very wonderfully the construction of the eye has been imitated in a photographic camera. The front lens is practically the equivalent of those three refractive media of the eye, the aqueous and vitreous humours, and the crystalline lens; whilst the iris, which in the eye serves to limit the amount of light entering it, has its exact representative in the "stop," which serves the same end in the camera. The photographic plate is, it need hardly be said, the counterpart of the retina, and has consequently been beautifully described as "a retina which does not forget." Similarly there is just such an arrangement for focusing the light as exists in the eye. In fact a camera is a rather better machine altogether than the eye, because the range is greater, and the focusing power is not lost as age increases. Therefore the artificial eyes of our camera are never in need of spectacles.

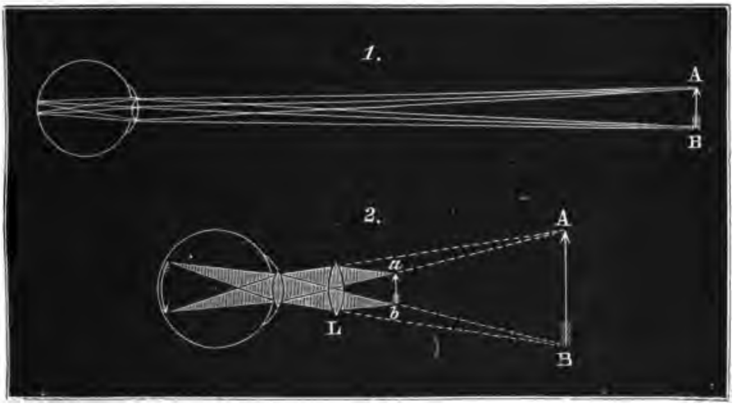

FIG. 12.—1. Diagram showing path of rays when viewing an object at an easy distance. 2. Object brought close to eye when the lens L is required to assist the eye-lens to observe the image when the image is magnified.

How optics enable us to read fine verniers.

This knowledge having been acquired, how is it to be utilised for the purpose of the measurement of angular space? It may be utilised in this way. The reason that we cannot clearly distinguish objects placed very close to the eye is, that the rays of light which flow from them are so extremely divergent that the crystalline lens cannot focus them on the retina. But by placing between the eye and the object a convex lens, that is a lens like the crystalline lens of the eye, this extreme divergence is corrected; the crystalline lens is thus aided, and the rays of light are brought to a focus, as shown in the lower part of Fig 12. Take the case of a vernier whose divisions are so fine that they are not visible at the distance of distinct vision, say about ten inches. If we attempt to correct this by making the divisions appear larger, by bringing the vernier close to the eye, we lose the power of focusing the rays which flow from it. But the introduction of a convex lens between the vernier and the eye enables the eye to see the division quite distinctly.

Of course the more nearly an object approaches the eye, the more powerful must be the lens, in order that the eye may clearly see it. In this way we see that the simple addition of a convex lens has enormously increased our power of observing and measuring small angles.

Action of a convex lens.

One can, however, go further than this, and use not one simple lens, but a combination of lenses. But before discussing the various combinations of lenses which are employed in various instruments, it is necessary to look a little more closely than we have yet done at the structure and action of our convex lens. Let us use a glass lens in conjunction with an electric lamp. Then we may get an image of the carbon poles thrown on the screen, in exactly the same way that the crystalline lens forms its image on the retina. But there is this important difference, that while the image formed by the crystalline lens is a clear and distinct one, that formed by our glass lens is a very bad one. Instead of the poles of the electric arc being clearly and sharply defined, they really appear as if seen in a haze, and are surrounded by coloured fringes of light, so that not much can be made of them. Why is this?

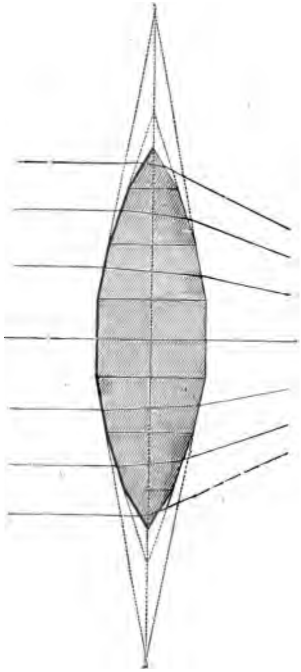

FIG. 13.—Formation of a double convex lens from sections of prisms. In this figure a few such prisms are shown, but the number may be imagined to be infinite.

We find by experiment that this attempt to imitate the action of the eye by means of such a simple glass lens is an incorrect way of proceeding, the eye possessing certain qualities which the simple glass lens does not. Although a lens seems to be a very simple matter, its structure is really based upon some

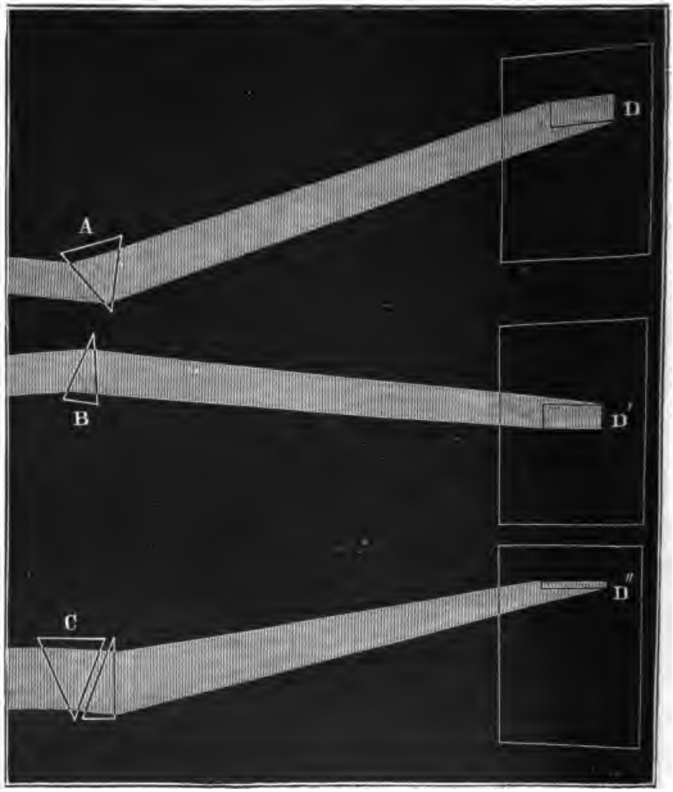

FIG. 14.—Diagram explaining the formation of an achromatic lens. A, crown-glass prism; B, flint-glass prism of less angle, but giving the same amount of colour; C, the two prisms combined, giving a colourless yet deviated band of light at D''.

very complicated considerations. If a section of it be taken it will be seen that its surface is built up of sections of triangular pieces of glass, these triangular pieces of glass being called prisms, and it is very important for us to know how they deal with the light. If in front of the beam of light issuing from the lantern a prism be interposed, it will be found that whilst part of the light is reflected from its first surface another portion, which is said to be refracted, is bent out of its original course by the prism. Further, it not only suffers this deviation due to refraction, but it undergoes also what is called dispersion. In fact, where the light falls on the screen an infinite number of different colours is seen, these forming what is called a spectrum. This is one of the reasons why such a glass lens as we have used will not perform the finer work of the eye; the images of the poles are surrounded by a false glow, because there is this power of dispersion which breaks the compound white light up into a number of its different elementary colours.

It is this power of deviation which the lens possesses which enables it to bend the rays differently according to their different distances from its centre, and causes them to form an image at what is termed the focus of the lens. The rays of light passing through the parts of the lens near the edge undergo more deviation in order that they may be brought to a focus at the same point as the other rays. A reference to Fig. 13 will show that this part of the lens is a section of a prism with a wider angle.

Now prisms which are made of different material, although they be of the same size and of the same angle, produce different deviations and different dispersions of the light which falls upon them.

The achromatic lens.

This fact has been taken advantage of in the construction of lenses. Let us take an illustration of the way in which this has been done.

Imagine glass which gives a high dispersion and but slight deviation, set to work against glass giving great deviation with but little dispersion. It is obvious that it is quite possible by a combination of that character to keep the deviation and get rid of the dispersion, or keep the dispersion and get rid of the deviation, as may be desired. By doing this a lens or artificial eye of great excellence may be made.

Suppose two different kinds of glass so combined as to form a prism, which should give a white image (see Fig. 14). Then the dispersion will have been got rid of, and the deviation will have been retained, and this is exactly what takes place in the modern compound or, as it is called, achromatic lens. By building up a lens in this way we can get a much better image of the carbon poles of the lamp than before, and we may make it build up an image at any distance from it, that is to say we may give it any focal length we please. This compound, achromatic lens, when used in a combination, is called the object-glass, because it is nearest the object. But when using such a lens as this for purposes of vision, there is something else to be considered besides the mere formation of images. It is not enough to consider this only, because when we spoke of the action of a convex lens in aiding us to read the vernier, we found that if an image was to be obtained in the eye, the rays entering it must be practically parallel. Now the image thrown by such a long focus lens may be regarded as a thing to be seen and examined like the vernier. And we must treat this aërial image as we treated the vernier, that is, we must interpose a lens.

The telescope.

In combining lenses together, then, it is important to bear in mind the fact that the rays of light which, after passing through the lenses ultimately reach the eye, must be parallel ones. Let us consider that arrangement which obtains in the telescope. In the simple form of this instrument, A (Fig. 15), representing the object-glass, receives the rays of light and forms an image of a distant arrow, from which they are supposed to flow, in exactly the same way that the lens we used just now formed an image of the carbon poles on the screen.

Remember now the way in which the eye was enabled to read the vernier placed close to it, and the action of the convex eyepiece C of the telescope will be obvious. In just the same way as the divergent rays coming from the vernier were grasped by the convex lens, and rendered parallel, so in this case the convex eyepiece of the telescope grasps the rays diverging from the image, reduces them to the necessary condition of parallelism, and enables the image of the object to be clearly formed upon the retina of the observer's eye.

We have, then, got so far: By means of an object-glass we produce an aërial image, and by means of a convex lens we view this image under conditions which enable another image of it to be formed on the retina. It is at once obvious that we can do something more than this, for if we place a concrete thing such as a cross wire at the same distance in front of the convex lens as the aërial image, or, in other words, at the focal distance of the object-glass, we shall see both the aërial image and the concrete thing, be it a cross wire or what not, both together. Now imagine that we can obtain an aërial image in this way of a star, and that side by side with this image of the star we observe such a cross wire. It is quite clear that if we have any means of getting the cross wire to bisect the image of the star we shall have a much more accurate method of pointing at any celestial body, and therefore of measuring the angle between two celestial bodies, than was possible on the old system of sights without telescopes.

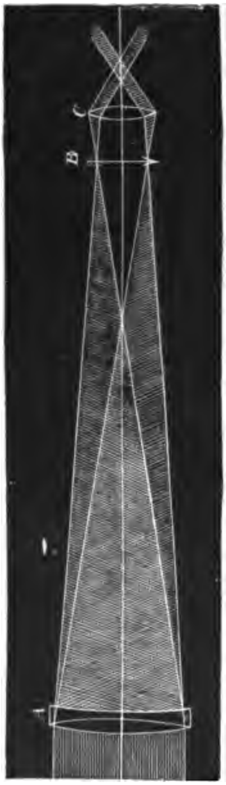

FIG. 15.—Telescope. A, object-glass, giving an image at B; C, lens for magnifying image B.

Suppose this telescope of ours to supplant the pointer of the old instrument of Tycho Brahe, consider the extreme accuracy of its observation as compared with that of the pointer in Tycho's quadrant, and it will be seen how vastly the application of these optical principles has added to the instrumental powers of the astronomer.

How optics enables us to replace the vernier by a micrometer.

But we have not yet done with optical applications. Its principles have been applied in yet another manner, but still, like these two applications which we have considered, tending to increase the power of accurately measuring minute angular distances of space.

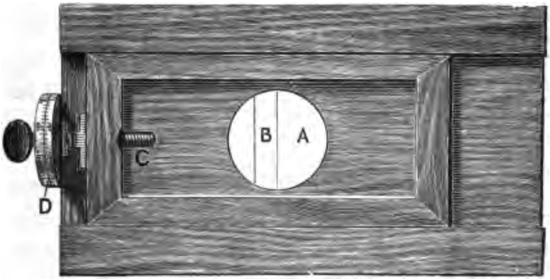

FIG. 16.—Model of micrometer.

Fig. 16 shows a simple model which has been designed to illustrate the principle of the instrument called the micrometer. This instrument places in the hands of the astronomer the power of measuring with extreme accuracy the most minute distances. It consists of two vertical wires, one, A, fixed, the other, B, movable by the rotation of a very perfectly cut screw, seen at C. The head of the screw, D, is divided into 100 parts, and read by means of a vernier to 1/1000ths.

This system of threads moving over certain small distances which can be accurately measured by means of a micrometer screw, can replace the cross wires to which we have just referred, and there are two very notable applications of this principle to which reference must now be made. When the object-glass is used for astronomical purposes, it is naturally arranged to bring the rays which fall upon it from a celestial body, and which are practically parallel, to a focus which represents the actual focus of the lens for such rays, and which is called the principal focus. But it is not necessary that the rays which fall upon such a lens should be parallel. The lens acts under other conditions, with this proviso, that the more the rays diverge from the body in front of it, or, in other words, the nearer the object is to it, the greater will be the distance behind the lens of the point at which the aërial image is formed.

Here in a few words we have a statement of the arrangement used in the microscope, and a moment's thought will show that such an arrangement may be applied to the vernier instead of the small lens, to which reference has already been made. Nay, we can go further than this. It may be applied to the circle itself, and help us to measure small fractional divisions of its parts with yet greater accuracy than is possible by the aid of the vernier. The way in which this is managed is as follows:—The microscope is pointed towards the circle, so that its divisions may be plainly seen in the field of view, and the position of the wire, on, or between, any division may represent a certain position which is to be measured by means of the circle. The micrometer head may now be used to tell us the exact distance in 1/1000ths of a revolution between the position occupied by the wire in the first instance, and the position of the wire when it exactly lies on the next division. By determining, according to the graduation of the circle, the number of thousandths of parts as indicated by the micrometer which lie between each division, it is obvious that the exact angular distance between such a position and the next division of the circle can be accurately determined. Such an operation as this is called a "run," and practically such a system as this is adopted in reading all large circles. But when it is a question of measuring smaller arcs, the micrometer may be used with the telescope itself, its wires appearing with the image of the object in the field of view.

A lamp demonstration.

A description of an experiment will perhaps convey a better idea of what can be done in this way. Fig. 17 represents the arrangement. The condensing lens of the lantern having been removed, the light is allowed to impinge upon a lens, A, placed at a short distance from the lantern. Its action on the light causes a reversed image of the poles to be produced in the air. The light coming from this image is then made to pass through another lens, B; the reversal is corrected, and a magnified image of the poles of the electric arc is thrown upon the screen. The first lens which forms the image may be regarded as the object-glass of a telescope, whilst the other lens which throws the magnified image upon the screen is the counterpart of the telescope's eyepiece. Now if at C, where the image is formed in the air, the micrometer wires are placed, they, as well as the image of the poles, will appear magnified on the screen.

In a precisely similar manner bodies may be made to appear as well as the wires of a micrometer in the field of vision of a telescope, and their diameters and the dimensions of different parts of them may be most accurately determined. Up to the present time we have been concerned simply with accurately determining the positions occupied by the various bodies which people space; but with this micrometer in the field of view of the telescope something more than this may be done. We may now make measurements upon the bodies whose positions alone we have been considering up to now. For instance, the image of a planet may be grasped by the wires, one wire bounding

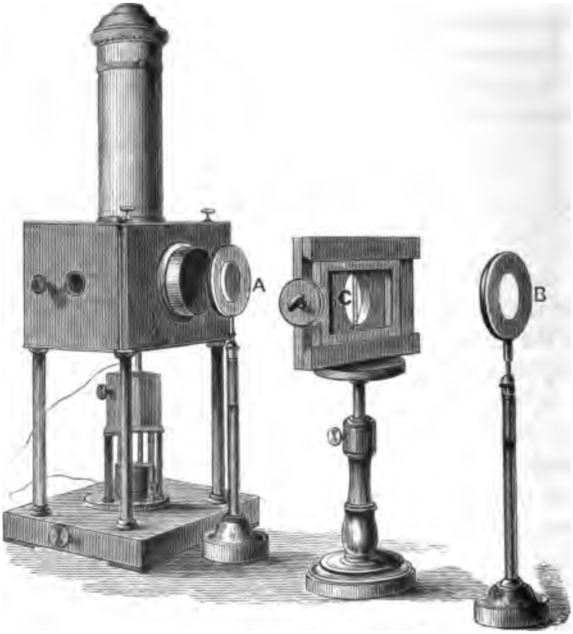

FIG. 17.—Micrometer arranged for demonstration with the electric light.

one limb of the planet, the other wire lying along the other limb. Then, knowing how many complete turns, and 1/100ths, and 1/1000ths parts of a turn have been given to the head of the screw in order that the wires may be separated through such a distance, and knowing also the value of these divisions in seconds of arc, the diameter of the planet may be measured. In like manner, the heights of lunar mountains may be ascertained by measuring the lengths of the shadows thrown by them. Or it may be a question of the distance between two stars close together. The method is still the same. One star is made to lie along the movable wire, the other is seen on the fixed one, and the distance through which the wires are separated is ascertained. Having attained to this, we may now bring our inquiry into angular measurement to a close.

In passing, as we shall next do, from the measurement of space to the measurement of time, it will be found that the difficulties have been grappled with very much in the same way. In this measurement of space we began with simple instruments, and only by a slow growth has the modern method been arrived at; yet notwithstanding the immense changes that have taken place, the pointer and circle of the old instrument are still represented in the new, whilst the vernier and micrometer, still pre-eminent, enable a degree of fineness in reading to be attained quite unparalleled in the old days. But in passing from these older instruments, in which the circle was so prominent a feature, and the pointer so small a one, to the more modern instruments, it will be seen that, although both are still preserved in some, a great change has taken place. The pointer, represented by the telescope, is the prominent part of the instrument, whilst the circle is greatly reduced in dimensions because it is so much more perfect.

It has been shown how, by the application of geometrical and optical principles, the measurement of angular space has been carried down to the 1/1000th of a second of arc, such a quantity being 1/1,296,000,000th part of an entire circumference, and when such an accuracy as this has been attained, and the altitude or the azimuth of the sun, or moon, or any other heavenly body, can be correctly stated with this exactitude, it will be seen how much better off in the way of defining positions is the modern astronomer than was Hipparchus with his 1/3rd, and Tycho Brahe with his 1/4th of a degree. To do this, however, is not enough. It is not only necessary accurately to define the position of a heavenly body, it is necessary also to know at what particular time it occupied that position. The next thing to be done, then, is to see how far we moderns have got in another kind of measurement, no longer the measurement of arc—the measurement of angular distance—but the measurement of *time*.

CHAPTER II.

THE MEASUREMENT OF TIME.

Early methods

THE measurement of time, we shall find, is not so simple a matter as is the measurement of space. A certain angular measurement of space, or the angular distance between two bodies, whether the distance be a degree, or a minute, or a second, is a very definite thing, having a beginning and an end; but time, so far as we can conceive, has neither beginning nor end; so that the problem of the measurement of time has to be attacked rather in a different way. Here again it will be as well that the matter should be studied historically.

What more natural than that man having got the idea of the flow of time, should have begun to measure it by the flow of water or the flow of sand? The earliest time measurers were really made in this way; water or sand being allowed to drop from one receptacle to another. There were difficulties, however, in thus determining the flow of time. In the first place the thing was always wanting to be wound up, so to speak, something was necessary to continue the action, and to prolong it; and the first appeal to mechanical principles was made with that view.

The first real clock put up in England was put up in Old Palace Yard, in the year 1288, by the Lord Chief Justice of that time, who had to pay the expense of it as a fine for some fault he had committed. Its construction was somewhat after this wise. One method of dealing with the flow of time was to call in the aid of wheelwork; but, as is well known, if a weight acts upon a train of wheels the velocity increases as the rotation is set up. Therefore the science of mechanics was called in to supply some principle which could be applied to prevent this unequal velocity of a train of wheels. Consider the arrangement shown in Fig. 18.

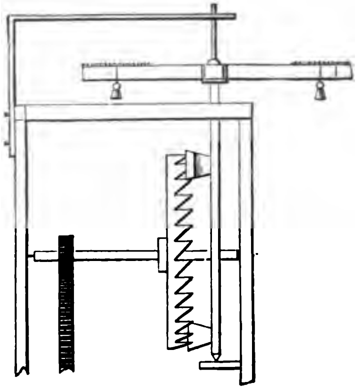

FIG. 18.—Ancient clock escapement.

The wheelwork train is capable of being driven by a falling weight. On the same axis as the smallest wheel, and therefore the one which turns most rapidly, will be seen another wheel provided with saw-like teeth. Then at the top is a weighted cross-bar, from the centre of which a perpendicular rod, provided with pallets, comes down to engage the teeth of the pallet-wheel. Now suppose the clock to be started. The weight is allowed to fall, and the wheels, including the pallet-wheel, begin to revolve; then begins a reciprocating action between the swinging bar and the wheel with which it acts, because the pallets, which are on either side of the centre of motion, act on the bar and drive it first in one direction and then in the other. The teeth of the pallet-wheel are continually coming into contact with the pallets of the swinging bar. First suppose that one of the teeth has encountered the upper pallet; it pushes this aside, and swings the bar in one direction. No sooner, however, has this been done than another tooth in the wheel encounters the pallet at the bottom of the bar and swings it in the opposite direction. In this way it is obvious that the bar is continually meeting and being met by the teeth of the rotating wheel, swinging first in one direction, and then in the other, the result of this reciprocal action being to prevent the increase in the velocity of the wheels which would otherwise take place.

It is in this way, then, by the performance at constant definite intervals of an equally constant definite amount of work, that the regularity of action of the clock is produced. The greater the distance of the weights on the cross-bar from its centre of motion, the longer will the bar take in swinging, the slower will be the action of the clock; so that the clock may be regulated by altering the position of these weights, bringing them nearer to, or removing them further from the centre of motion of the bar, according as it is desired to hasten or retard the action of the clock's mechanism. Yet at whatever distance from the centre of motion the two weights be placed, assuming always that they are both at the same distance from it, there is still this constantly-recurring performance, at equal intervals, of an equal amount of work which produces the regular action of the clock. This was the kind of clock then which was put up in Old Palace Yard. But that did not go well enough, giving such inaccurate results that Tycho Brahe had to discontinue the use of this arrangement.

Galileo and Huyghens.

Fortunately however for science some few years later two most eminent men, Galileo and Huyghens, had their attention drawn to this very problem. The first of these, Galileo, was at that time studying medicine. He happened one day to be at the cathedral at Pisa, where, it will be remembered, they have a most beautiful lamp which swings from a great height in the cathedral. Galileo was at this time working at that branch of his medical studies which deals with the pulse, and he looked at this lamp and found that its swinging was perfectly regular. To-day perhaps it may seem very natural that this should be so, but Galileo had the advantage of being before us, and that is why it did not seem quite so natural to him. There was at that time no known reason why it should swing in perfectly regular rhythm. He found that the lamp when swinging, no matter with what amplitude, took practically the same time for each swing, timing it by his pulse. His idea was that this would be an admirable method of determining the rate of a man's pulse, and the first clock on this principle was constructed from that medical point of view, being called a Pulsilogium. Some years afterwards, however, the extreme importance of such an arrangement from an astronomical standpoint became obvious, and very much attention was given to it. It is unnecessary to add that this swinging body nowadays is called a pendulum. The most perfect pendulum made in those early days is represented in Fig. 19.

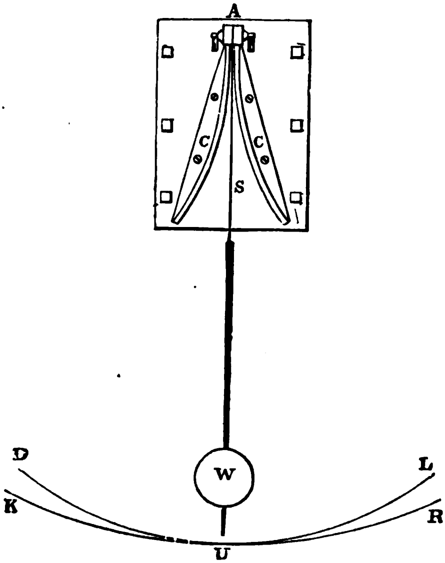

FIG. 19.—Cycloidal pendulum.

The fundamental difference between that and the modern pendulum is that part of the pendulum between S and A was elastic. It was made elastic for the reason that although

Galileo could not find any difference between the times of the oscillations of the lamp in Pisa Cathedral, according as its amplitude of swing was large or small, yet such a difference did exist, although it was only a slight one; and the only method of getting a perfect pendulum which should make its swing in exactly equal times, independent of its arc of oscillation, was to construct this so-called cycloidal pendulum. It was so named because in its swing its elastic portion was held by the curved guides seen in the figure, and made to bend in that particular curve. By this means the pendulum instead of swinging through the arc, K U R, was made to oscillate through D U L, since when the pendulum was at the points D and L, it was practically a shorter pendulum than when at rest. In other words, whilst the pendulum was swinging from U to D and from U to L, its curvature, and consequently its vibrating length was continually changing. In that way, by continually varying the length of the swinging part, it was found possible to make a pendulum which, independent of the length of its arc of oscillation, would make its swing in times which for all practical purposes were absolutely equal in length. That was the most perfect pendulum of that time. Nowadays, the cycloidal pendulum has been replaced by one which swings through a very small arc, and the continual shortening during the oscillation in the cycloidal pendulum is by this means dispensed with, whilst the friction also being much reduced, there is less interference from that source. With this very small swing the difference between the arc of the circle described and the cycloid in which the cycloidal pendulum swung is practically indistinguishable.

The modern clock.

The great difference between the modern clock and the ancient one is that in the former the pendulum is interfered with as little as possible whilst swinging, and makes each swing under precisely similar conditions. To attain this is to have done much. In the first place, if the clock has a heavy weight, that weight will probably interfere a good deal with the swinging of the pendulum. The clockweight, therefore, must be as light as possible. Secondly, if the wheelwork is always in contact with the pendulum, this also will interfere with its free and natural movement. There must be, then, an arrangement so that the wheelwork shall be brought into contact with the pendulum only for the shortest possible time. Thirdly, it must be remembered that the different substances which it is most convenient to use in the construction of pendulums, vary their dimensions with the variations of the temperature and moisture of the air in which they are placed, and great care must be taken to eliminate any errors which might arise from such a source. How are these various conditions complied with ? The first, that the clockweight must be small, is not difficult to adhere to; but it will be well to consider the way in which the second condition, that the action between wheelwork and pendulum shall be the least possible, is met. This is done by employing what is called an escapement. It is so named because the pendulum in its swing is allowed to escape from the wheelwork, and thus retain a perfect freedom. The particular form of escapement about to be described is that which, for a reason that will appear immediately, is called the dead-beat escapement (see Fig. 20).

The escape wheel is the modern representative of the toothed wheel of the old clock, whilst the projections W

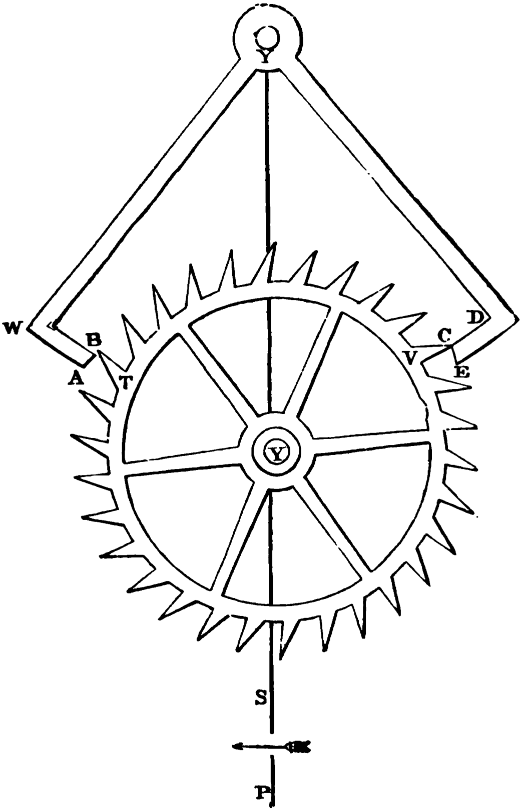

FIG. 20.—Dead-beat escapement.

and D are modifications of the pallets on the swinging bar in that instrument. Let the pendulum move in the direction of the arrow. The tooth T has just been released, thus permitting the tooth V to engage the other pallet D. Now whilst the tooth remains on the pallet, the escape wheel remains locked, while the pendulum is quite free to swing, there being nothing to retard it save the very slight friction between the tooth and the surface of the pallet. The rotation of the escape wheels, however, brings the tooth on to the oblique edge of the pallet, and with it in this position the pendulum is aided in its forward swing. Then the pallet escapes, receiving an impulse, but since this is received almost as much before the pendulum has reached its vertical position as after it has passed that point, no increase or diminution in the time of its oscillation takes place. It is in this way that the second of our conditions is complied with, the wheelwork being effectually prevented from interfering with the regularity of the pendulum's swing. It is called the dead-beat escapement, because when the tooth falls on the circular portion of the pallet and locks the escape wheel, the seconds-hand fitted to it stops dead without recoil, because the arc of the surface of the pallet is struck from the centre of motion. In an astronomical clock a still more modern form of escapement, called the gravity escapement, is sometimes employed.

It will perhaps be convenient at this stage to compare the fineness of the division of time given by a clock of this description with the fineness of the division of the second of arc we have already discussed. There is, however, a little difficulty about this, because at present there seems to be no special reason why any particular unit of time should be selected. Ordinarily a day is divided into twenty-four hours, each of these twenty-four hours is subdivided into sixty minutes, these again being each divided into as many seconds. The origin of this division of time will be seen later on; for the present let the fact remain that it is so.

Now a modern clock beats practically true seconds, and astronomers after a little practice gain the power of mentally breaking that second up into ten divisions, each of which is of course one-tenth of a second, so that we can say that a day may be divided into 864,000 parts, and in this way institute a comparison of the fineness of the division of time with those minute measurements of angular space with which we so recently dealt.

The chronometer.

It is a familiar fact that the length of a pendulum which vibrates seconds is some thirty-nine inches, and it is easy to understand that there are many conditions in which a clock of this kind, with its pendulum of more than a yard long, cannot be used. Not only indeed is there this inconvenient length of the pendulum, but it is necessary that the clock to which it belongs should be rigidly fixed in an upright position. The question therefore arises, is this clock which deals out seconds so accurately the only piece of mechanism that can record and divide our time, or is any other time-measuring instrument available? Fig. 21 shows part of such an instrument, known as the chronometer, in which, whilst the principles necessary to be followed in the construction of the clock have been adhered to, the pendulum has been dispensed with, and the perfect stability and verticality of position so important to the clock, are here unnecessary.

In this instrument the pallets of the dead-beat escapement have been replaced by a detent, D. Let us consider the action. The escape-wheel, S, is advancing in the direction of the hands of a clock. One of its teeth meets the detent, and the wheel is locked. Then what happens is this: when the balance-wheel, R_1, swings, the circle, R_2, centred on it shares its motion. This, it will be seen, is armed with a little projection P_2.

We left the escape-wheel locked. Now assume that the balance-wheel is swinging in the direction of the arrow. It carries the small circle with it, and the piece, P_2, in its motion, coming into contact with the end of the spring, seen projecting beyond the arm of the detent, raises it and the detent, so releasing the tooth of the escape-wheel. The slight retardation which the balance receives in consequence of this action is immediately compensated. The moment the escape-wheel moves on again, one of its teeth meets the projection, P_1, and the balance-wheel receiving this fresh impulse goes on to complete its swing. Then it returns and

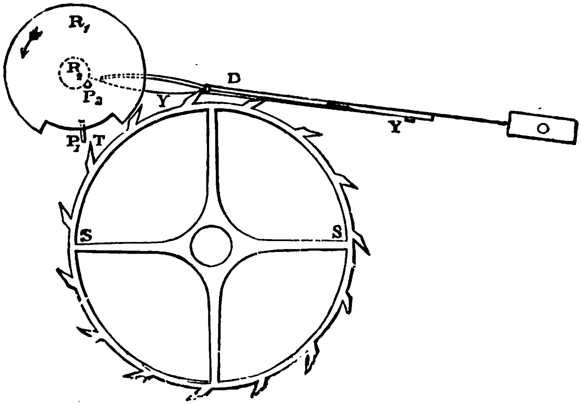

FIG. 21.—Chronometer escapement.

swings in the opposite direction, this time without acting in any way on the detent. When the balance-wheel made its first swing and the point P_2 met the projecting end of the spring, the latter could then only bend from the end of the arm with which the detent is provided and against which the point P_2 forced it. But on the return swing the spring is found capable of bending from the more distant point of its attachment to the shank of the locking-piece. It is therefore easily pushed aside; there is no change in the position of the detent, nor is any resistance offered to the motion of the balance-wheel, which goes on to complete its swing. Then another tooth is caught, the escape-wheel is again locked, and again released by the lifting of the detent; so the action goes on, the teeth of the escape-wheel being constantly detained, and as constantly released by the action of the point P_2. The balance-wheel, it will be noted, receives its impulse only at every alternate swing, whereas in the clock the pendulum receives its impulse at each vibration.

The chronograph.

Time then can be divided down to the 1/10th of a second, or as we expressed it, down to the 864,000th part of a day, not only by a clock, but also by this chronometer. Having obtained this 1/10th of a second by these instruments, the question arises as to whether it be possible to get a still finer division. It will be seen that a very much finer division than this can be obtained, the 1/100th part of a second being a measurable quantity; not that such a small fraction of time as this is ever necessary in astronomy, nor will it be until the present astronomical methods have been replaced. If it were possible to get all observations made by photography, then it would be worth while recording with such minuteness, because photography would always behave in the same way, whereas two observers never have the same idea as to the time of occurrence of any phenomenon which they observe. Yet, although so great an accuracy as this is not attempted, it will be quite worth while to consider the means by which this exquisite fineness of the division of a second of time has been arrived at. We shall see that just in the same way as an appeal to mechanical principles resulted in an improvement in the construction of our clock, so this fineness in the division of time has been obtained by an appeal to the principles of electricity. Let it be assumed that the seconds pendulum of our clock swings with perfect accuracy and with absolute uniformity from second to second, in spite of changes of temperature and other perturbing influences; and having assumed this, let us see how electricity can be made to aid in the measurement of time. The instrument used is called a chronograph. It consists of a metal cylinder revolving by clockwork, and covered with cloth, over which a piece of paper can be stretched. Below the cylinder and parallel with it is a track along which a frame carrying two electromagnetic markers or prickers is made to travel uniformly by the same clock that drives the cylinder. Wires connected with a battery lead from one of these magnets to a clock and from the other to a key, which can be depressed whenever an observation is made, and a current so sent to the magnet. The effect of this is to cause it instantaneously to attract its iron armature and cause the pricker with which it is connected to make a mark on the paper above.

The connection of the chronograph with the clock is as follows:—The bearing shown in the middle of the diagram (Fig. 22) is a continuation of the bearing on which the seconds hand of the clock is supported, and there is a little wheel which does its work quietly at the back of the clock in exactly the same way that the seconds hand does its work quietly in front of it. What that wheel does is this. Every time that each of its teeth—and there are sixty of them—comes to the top of the wheel it touches a little spring. That little spring then makes electrical contact, and a current is sent flowing through parts of the apparatus already described. Now the teeth in that wheel, being regularly disposed around its circumference, always succeed one another after exactly the same interval of time, and there is no difference or distinction from second to second, or from minute to minute. But suppose that before the clock is started one of these teeth is filed off, and so filed off that

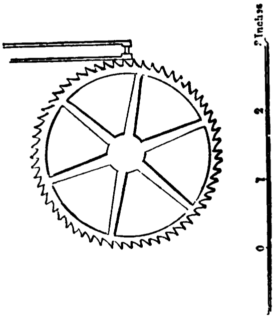

FIG. 22.—Electrical contact apparatus at back of clock.

when the seconds hand points to 0 seconds, and the minute hand to a completed minute, this part of the wheel shall be at the top, and there shall be no electrical contact established, for the reason that the tooth of the wheel is not there to act on the spring. In that way it is easy to manage matters so that the beginning of each minute shall be distinguished from all the other fifty-nine seconds which make up the minute. Let the cylinder, covered with paper, revolve once in a minute. In that case, the electrical current will make a hole or a mark on that paper every second, and as matters are so arranged that the prickers shall be travelling along at the time that the dots are made upon the revolving paper they are thus made along a continuous spiral, and since we have supposed the cylinder to revolve once in a minute, the beginning of each minute will be in the same line along the spiral. Then, according to the diameter of the cylinder, a second of time will be represented by the distance between two consecutive dots, sixty of them round the cylinder representing sixty seconds. Suppose now that a man with a perfect eye makes an observation, recording it by sending a current through the apparatus and making an extra dot in its proper place beside the line of dots impressed by the clock at each second on the paper. He will then have an opportunity of observing on the paper the precise relation of the dot which represents the time at which the observation was made to the other dots which represent the various seconds dotted out by the clock, and not only the exact distance of the observation prick from the nearest *second*, whether it be 1/20th, or 1/10th, or 1/100th of the distance between that second and the next, but the omission of the record of the first second in the minute will give the relation that observation has to the nearest *minute*.

For the sake of simplicity the case of one observer making one observation has alone been considered; but if the work be properly arranged, then not only one electro-magnet, but two, or three, or four, may be at work upon the same cylinder at the same time, each making its record, and that is how such work is being done at the Greenwich Observatory.

CHAPTER III.

OBSERVING CONDITIONS.

The earth is a sphere.

THIS power of measuring and dividing time then having been obtained, we seem to have reached our subject, "The Earth's Movements." Yet even now there are one or two other matters which require to be discussed before we consider the movements themselves. The first of these is the important fact that the earth is spherical in its form. There have been many views held at different times as to the real shape of the earth, but the only view we need consider is that stated. In going down the river in a steamboat, or, better still, in standing upon the sea-shore at some place, such as Ramsgate, where there are cliffs, and where, consequently, one may get from the sea-level to some height above it, very quickly it is observed that when any ship disappears from our view by reason of its distance, it seems to disappear as if it were passing over a gentle hill.

It does this in whatever direction it goes. This familiar fact is a clear proof that the earth is a sphere, and is so obvious that it may seem unnecessary to mention it, but it was as well to do so for a reason which will appear shortly.

Another obvious demonstration familiar to all who have travelled is, that whenever we considerably change our latitude, the well-known stars no longer appear at the same altitude when they cross the meridian. So that such familiar northern constellations as the Great Bear, or Charles's Wain, and the Pole Star itself, gradually get lower and lower until they scarcely appear above the horizon as we get nearer and nearer the equator. On the other hand, stars which one who has lived all his life in England has never seen, burst upon his sight; he finds, as it were, a new heaven revealed to him by simply travelling about this round globe.

Besides this argument in favour of the spherical shape of the earth, there is the argument from analogy: the moon is round, the sun is round, all the known planets are round. The stars are so infinitely removed from us that it cannot be determined whether they also are spherical, but doubtless they are as round as the earth. This point of the tremendous distance of the stars is an important one to bear in mind. Their distance cannot be conveniently stated by thousands, nor even by millions of miles, it is something far greater than that. It may be asked why it is that such a statement can be thus positively made. For this reason: the stars have been observed now for many ages, and the historical records of ancient times show that the chief constellations, the chief groupings of stars, visible in the heavens now, were seen then. In the Book of Job, for instance, there is a reference to the well-known constellation of Orion, and there is very little doubt that for thousands and thousands of years that constellation has preserved the familiar appearance of its main features. The constellation called Charles's Wain, or the Great Bear, was also known to the ancients. If the stars were very near to the earth this could not happen. If they were close to us the smallest motion either of earth or star would at once change their apparent positions, and would prevent this fixity of appearance; the skies would be filled, not with the constellations which were known of old, but with new and ever-changing clusters of stars. This constancy of the constellations, not only from century to century, but from era to era, clearly proves, then, that the stars of which they are made up must be at an infinite distance from the earth.

The size of the earth.

The next point, then, is the size of this round globe. Its size has been determined, I have no doubt, to within a very few miles, in what appears to us now a very simple manner. In the first place, every section of the earth is bounded approximately by a circle, and, as we have seen, all circles are divided into 360 degrees. Hence, if we can measure accurately the 1/360th part of any one of these great circles, and if, when we have got that measure out into miles, we multiply it by 360, we get the circumference of the earth, that is to say, the whole distance round it. Then by dividing this result by something a little over 3 (3·1416, the ratio of the circumference of the circle to its diameter), we find out how far it is from one side of the earth to the other. This gives us the diameter of the earth. As a result of a long series of observations, which, however, we cannot discuss here, it has been found that a degree measures as near as possible, on the average, 69½ miles. It can be stated in inches, but it is near enough for me to give as a first statement of results that it is about 69½ miles; and if we take the trouble to multiply 69½ miles, the average length of one degree, by 360 degrees, the number of degrees that there are all round the earth, we find that the circumference is something like 25,000 miles, and therefore that the diameter of the earth is something like 8,000 miles.

Mark well the words "on the average." In truth the earth is flattened at the poles, so that the length of the degree varies from the pole to the equator; and hence the diameter in the equatorial plane is in excess of the diameter from pole to pole. These two diameters, expressed in feet, are as follows:—

Equatorial	41,851,734
Polar	41,708,954

We shall see in the sequel the meaning of this. There is another point. If we liken the earth to an orange, the orange must be a squeezed one. The equatorial diameter which passes through the earth from long. 8° 15′ west of Greenwich to the opposite points, is 6,096 feet longer than the one at right angles to it.

Parallax.

Having, then, an idea of the size of the earth, and therefore of the length of its diameter as compared with the distance between any two familiar places on it, let us next consider the question of the distance of the stars a little further. If two pieces of wood (see Fig. 23) joined together by a cross-piece be taken, a moment's thought will make it obvious that the angles which A B and C B make with the cross-piece A C, will vary with the distance of the body, which can be seen first by looking along A B and then by looking along C B. If these pointers be directed to a very near object in the room, they must be greatly inclined (as in 1). We say the object has a sensible *parallax*, and the greater the base A C, the greater the parallax will be. If something more distant be taken, there is less inclination [parallax], and if we could sight St. Paul's from South Kensington by looking first along A B and then C B, there would be still less. If something at a greater distance were sighted, say St. Giles's at Edinburgh, the inclination of A B

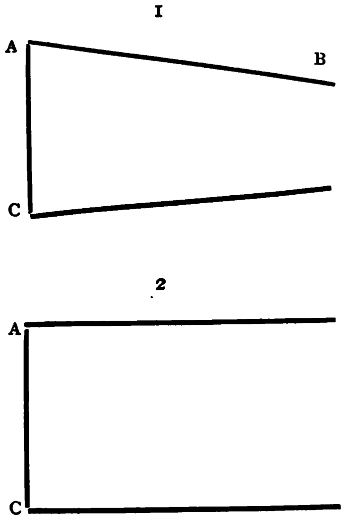

FIG. 23—Model to illustrate parallax.

and C B would be smaller than it was in the case of St. Paul's, because St. Giles's is at a much greater distance. It follows, then, that in sighting an object infinitely removed from us, the light from it will be in a condition of parallelism, and A B and C B consequently must be placed quite parallel in viewing it (see 2). That is another reason for saying that the stars are at an infinite distance from the earth because when A C is represented by the earth's diameter the stars appear in the same direction. Why it is so important to insist on this point will appear very clearly by and by.

The earth in space.

Now suppose that in the centre of a lecture-theatre a little globe were hung to represent the earth, the walls of the theatre and the people in it representing the heavens surrounding the earth. In such a case it is clear that the appearances presented would be the same whether the heavens moved round the earth, or the earth itself were endowed with motion. Let us, without making the assertion, assume that the earth does move. It is perfectly obvious, since the apparent motions of the heavens are so regular, that if that be so, she must move with wonderful constancy and regularity; she does not first move in one direction and at one inclination, and then at another; that would be very serious.

If she rotates she must rotate round some imaginary line called an axis. This introduces an important consideration, because, whether the earth itself rotates on an axis, or the heavens move round the earth—and in the latter case the heavens must also move round an axis—in either case the motion must be an equable one; so that if the matter is thus limited to a constant axial rotation, or a constant revolution as it would be called in the case of the stars, several things will happen. Let us take the former case, in which the earth itself moves. Then the motion of the surface of the earth will be least at those points which are nearest the ends of the axis on which it turns. Take the case of an observer at such a point, he will be carried a very little distance round during each rotation; similarly, if the stars move, a star near the ends of the axis round which the stars move will be carried a very little distance round during each revolution of the celestial sphere.

Experiments with a globe.

Change the position of the man on the earth from the pole to the equator. Then he will be carried a very considerable distance round in each rotation of the earth. Similarly with the stars; if they move, a star in the celestial equator will be carried round in a very long circular path during a revolution. That is the first point. Another point is that if we assume the earth to rotate, we must carefully consider the varying conditions which are brought about by the different positions of an inhabitant of the earth under those circumstances. For instance, take the case of a man at the equator: he looks at things from an equatorial point of view, and in the rotation of the earth he plunges straight up and straight down. Similarly, if the stars' daily revolution belongs not to the earth but to the stars, to an observer at the equator of the earth a star over the equator would appear to move straight up and straight down; and now in dealing with this question and endeavouring to ascertain whether it be the earth or the stars which move, it is most necessary to consider the relation of the movements or apparent movements of the stars to the place from which they are observed, and in so doing it is found that there is an immense difference between the conditions which obtain at the poles and at the equator with reference to the phenomena which are observable in each case.

Let us take a globe to represent the earth, and let London be considered the central point for our observations. In order to make an ordinary globe, representing the round earth, do this, we have to insert a metal rod, the two ends of which, as we all know, are generally fastened into a circle. The earth itself has no such interior economy as this, but it has something which does just as well, a mathematical line which is called the axis, and round this mathematical line the earth is perpetually rotating with constant speed. Now at all places on the earth, in whatever direction we look, we see an apparent meeting of earth and sky; and supposing our observation to be made on an extended plain or at sea, the surface of the earth or sea may for simplicity's sake be considered as a plane bounded by the circle where the earth and sky seem to meet. This is known as the circle of the horizon. To represent this, a piece of paper may be put over London on our globe (see Fig. 24), and London may be brought to the top. When that has been done, remembering that the stars are placed at so infinite a distance, the horizon which cuts the centre of the earth, and which is called the true horizon, represented by the wooden horizon of our globe, may be considered as being practically the same thing as the small sensible horizon of London, represented by our piece of paper when at the top of the globe, because then the two planes will be parallel. For, whether a star be seen from the equator or from London, owing to its tremendous distance it will appear to occupy the same position in space. Now let the globe be made to rotate, then the inclination of the plane of the horizon of any place, of our horizon of London for instance, is continually changing during the rotation (Fig. 24). An exception, however, must be made with

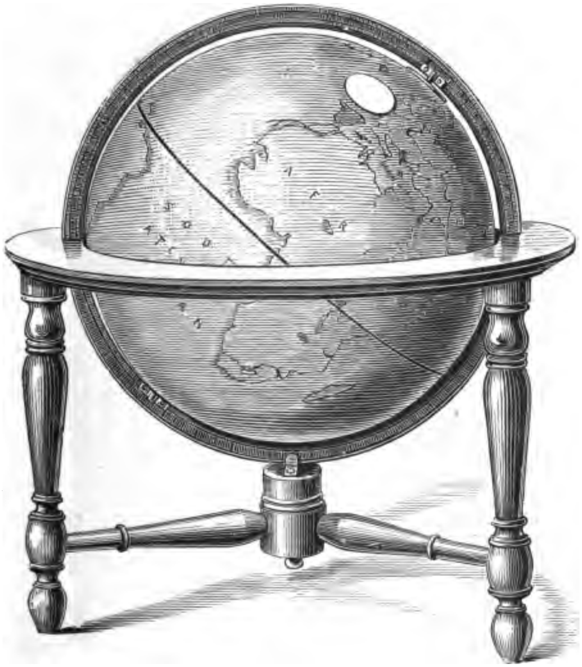

FIG. 24.—Diagram to show how the inclination of the horizon of London will change with the rotation of the earth.

regard to the poles of the earth. At these two points the inclination will be constant during the whole of the rotation.

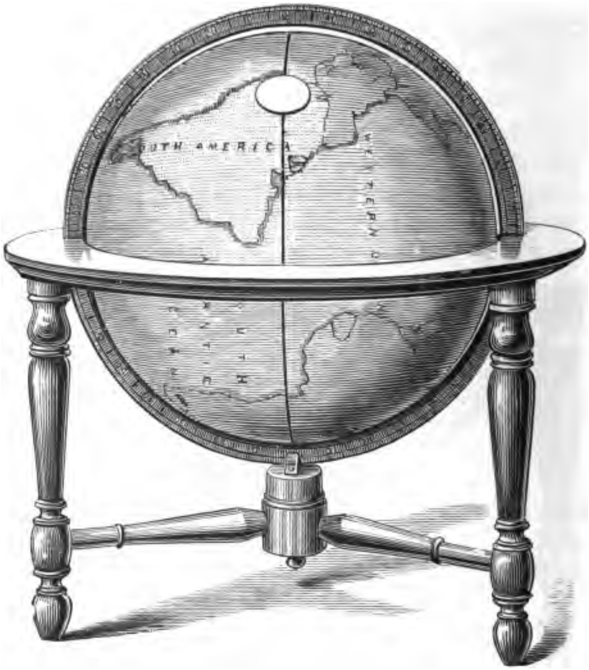

FIG. 25.—Diagram to show how the inclination of the horizon of a place on the equator changes in one direction only.

If now a point on the equator be brought to the top of the globe, it will be seen, as the globe is rotated, that the observer's horizon rapidly comes at right angles to its first position (see Fig. 25).

Such experiments as these will show that the conditions of observation at different parts of the earth's surface are very different, and this whether it be the earth or the stars which move.

The sphere of observation.

Let us now consider with a little greater detail the conditions which prevail in the latitude of London. Let London be again brought to the top of the globe. Let O (Fig. 26) represent an observer in the middle of the horizon, S W N E. Let Z be the zenith, which, of course, would be reached by a line starting from the centre of the earth, and passing straight up through the middle of the place of observation. S′ is a star, and we want to define its position. How can this be done? Imagine first a line drawn from the observer to the zenith. Imagine next another line going from the

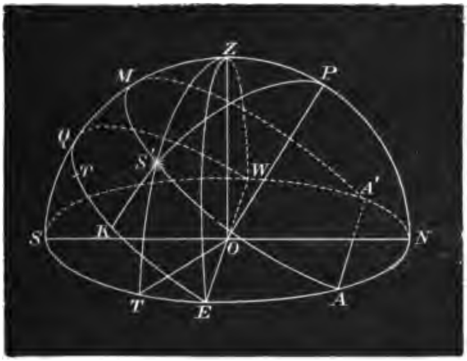

FIG. 26.—Observing condition at London.

observer to the star, or, what is the same thing, from the centre of the earth to the star. Then the angle inclosed by these two lines will give us the angular distance of that star from the zenith, or similarly we may take the angle included between imaginary lines joining observer with horizon and star, and thus obtain the star's altitude.

Again, suppose it be desired to define the star's position with reference, not to the zenith, but with reference to the pole of the heavens, that point where the earth's axis if prolonged into space would cut the skies. In that case since P in our diagram marks the position of the pole, a line P S′ will give what is called the polar distance of the star. If the angular distance of the star from the equator of the heavens W Q E be required, since the prolongation of P S′ would cut the equator, the distance from S′ to the point of intersection, K, will give the angular distance of the star from the equator; in other words its declination. Again, its position may be stated not only with regard to the zenith and to the horizon, but to some other point, say the north point. In that case a line or plane, Z S′ T, is imagined passing from the zenith through the star, and the distance between T and N will give the star's azimuth or angular distance from the north point of the horizon.

We have taken London, but of course each place on the earth has its sphere of observation, with its zenith and the north, east, south, and west points. With regard to the axes of the earth and the heavens, they both possess north and south points, and in the heavens as in the earth, the equator lies midway between them.

CHAPTER IV.

THE ROTATION OF THE EARTH.

How the rotation has been demonstrated.

THE several ideas concerning the movements of the earth which were introduced in the last chapter will in the present one have to be dealt with in greater detail.

It was then agreed that if the whole expanse of the heavens were to travel with a perfectly equable motion in one direction, such a motion for instance as would result from all the stars being fixed to a solid transparent substance like those crystal spheres that the ancients really believed to exist; or if, on the other hand, the earth herself, instead of being free to turn as she listed with varying velocity in any direction, really went with perfect constancy in the direction opposite to the apparent motion of the stars, the visible effects would be the same in both cases, so that an appeal to our eyes would not suffice to enable us to say whether the earth moved or whether she remained at rest while the celestial sphere revolved around her.

Under these circumstances what is to be done? It has been seen how, both with regard to the measurement of space and the measurement of time for astronomical purposes, those interested in the physics and beauties of the various classes of celestial bodies outside our own earth have picked and chosen now one bit of physical science and now another to help them in their inquiries; and with regard to this very important question, "Does the earth move or is she at rest?" we shall see how very beautifully and perfectly the rotation of the earth has been demonstrated by the application of certain mechanical principles.

The majority of people probably have some acquaintance, however slight, with machinery—with steam engines for instance; and it is a familiar fact how very important a part is played in the steam-engine by the flywheel. Why should that be? Why should this flywheel be so important that it is only quite recently that mechanicians have learned to do without it? For this reason: if a mass of matter such as a flywheel is once made to revolve, it will retain that motion for a long time, resisting any tendency to perform its motion in any plane but the initial one or to increase or decrease its velocity. Now, in a steam-engine, the first effect of the steam pressure is to give a to-and-fro straight-line motion to the piston-rod, and in order to make the power of this motion more generally useful, it is transformed to a circular motion by means of a crank and connecting-rod. Twice in each revolution the crank and connecting-rod will be in the same line, and the push or pull of the piston-rod will then be incapable of giving a rotatory motion to the crank, unless some special contrivance be employed. These dead points, as they are called, are got over by fixing a heavy flywheel to the crank shaft; this being once set in motion, goes on moving, in virtue of the property stated, and carries the crank over the dead points. The flywheel also acts in preventing the engine making too sudden a start. In addition to this, when we have a mass of matter in the condition of the revolving flywheel it has some very peculiar qualities, only observed when such a mass of matter is in motion. If, then, we have a wheel so arranged that a very rapid rotation is being imparted to it, it does not behave as it would when at rest. These properties possessed by a rotating body can be well shown by an instrument known as the gyroscope, of which we shall speak more fully later on. It consists essentially of a disk to which a very rapid rotation can be imparted by a train of wheels or by other means. If the disk be set rotating, it is found to possess those curious qualities of which I have spoken. If whilst rotating at a high velocity it be placed in the position shown in Fig. 27, it will not fall, but will take up a movement of revolution round the stand.

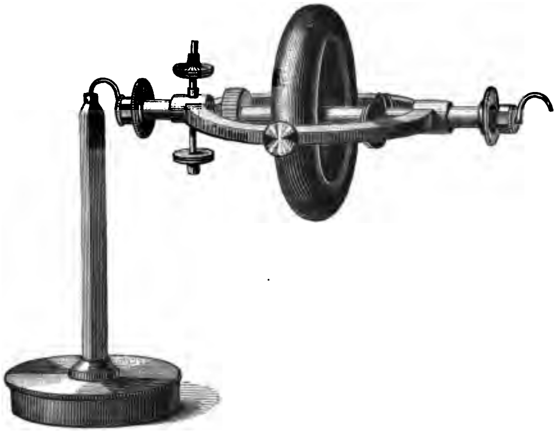

FIG. 27.—Rapidly-rotating wheel supported outside one end of its axis.

Foucault's experiments.

From considerations suggested by this and other similar experiments, Foucault pointed out that it might be demonstrated whether the earth moved or whether she remained at rest. It struck him that the problem should be attacked somewhat in this manner:—

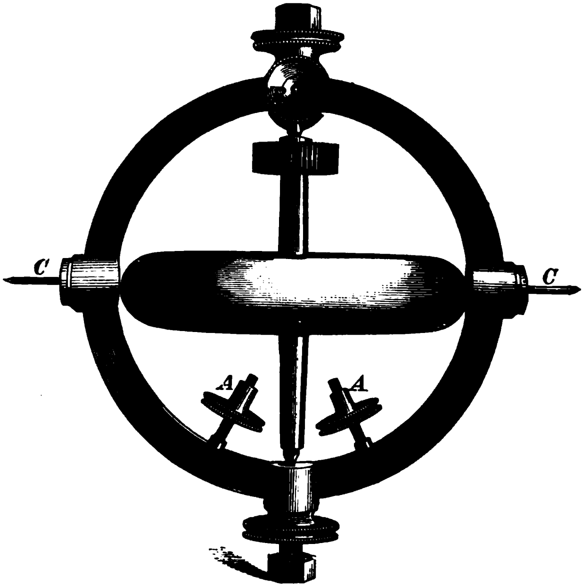

FIG. 28—Rotating disk or gyroscope. C C, knife edges; A A, B, adjusting weights.

Suppose the earth to be at rest, and that either at the north or south pole a pendulum, suspended so that its point of support had as little connection with the earth as possible —so that it should, in fact, like the rotating flywheel, be independent of external influences, were set vibrating. This pendulum would oscillate in a vertical plane which with regard to infinite space, and to the surface of the earth at rest, would be unchanging. Then an observer at the north or south pole would note that the swinging pendulum (the earth being considered as at rest) always had the same relation to the objects on his horizon. But, said Foucault, suppose that the earth does move. Then the swing of such a pendulum would not always be the same with regard to the places on the observer's horizon. Let the earth be represented by a globe. Suppose it to rotate from west to east. Place it with the north pole uppermost, and set the pendulum, whose point of support is disconnected from the rotating earth, swinging. Then the plane of the pendulum's motion will appear to travel from left to right as the earth rotates from right to left beneath it. Now suppose the pendulum to be suspended in the same way at the south pole, right and left now being changed. The earth of course rotates in the same direction as before, but the pendulum now appears to change the plane of its swing from right to left. At the equator the earth simply rotates straight up and straight down beneath the swinging pendulum.

From these considerations it became evident to Foucault that, if there were any possibility of demonstrating the movement of the earth by means of the pendulum, the demonstration would take this form. Provided it were possible to swing a pendulum so that it should be as free as possible from any influence due to the rotation of the earth, and to take that pendulum to the north pole, it would appear to make a complete swing round the earth in exactly the same time that it really takes the earth to make a complete rotation beneath it. At the south pole exactly the same thing would happen, except that the surface of the earth would appear to move in the opposite direction to what it did at the north pole. Now it will be perfectly clear that if we thus get a pendulum plane appearing to revolve one way on account of the true motion of the earth at the north pole and in the opposite direction on account of the true motion of the earth at the south pole; at the equator, it will not change the plane of swing either way, that is to say, the time taken by a pendulum to make a complete swing will, at the poles, define the true time of the earth's rotation, whilst at the equator it will be infinite.

At all places, therefore, between either pole and the equator the period of swing will be different, and the time taken to make a complete swing will increase or decrease as the equator is approached or receded from. So much for theoretical considerations. Can they be put to the test of experiment, and an answer obtained from nature herself?

The facts observed with pendulums.

The fact is that this idea of Foucault's is so beautifully simple that anybody can make the experiment providing he has the means of using a very long pendulum. This pendulum must be rigidly, but at the same time very independently, supported.

Beneath the pendulum, in contact with the earth, and therefore showing any movement of rotation which the latter may possess, is a board, on the centre of which the pendulum nearly rests. From the central point of this board lines are described showing so many degrees from the central line over which the pendulum bob swings. These preliminaries being arranged, let the pendulum be started. This is done by drawing it out of the vertical and tying it by a thread which is burnt when it is desired to start the experiment.

Then, in consequence of that quality, the existence of which was revealed to us by the rotating disk and which is possessed by this vibrating pendulum, and in consequence of the precautions which have been taken to prevent its swing being interfered with by the motion of the earth or other perturbing influences, it should be found, if Foucault's assumption be correct, that the earth is moving beneath the pendulum. And if all the conditions of the experiment have been complied with it is found that the pendulum moves over the scale as the earth rotates beneath it. That then is one demonstration of the existence of the earth's rotation.

The question now arises whether there be any other method of determining the same thing. There is, but in answering the question in the affirmative it must be said that this second method is neither so simple nor so satisfactory as the first.

We owe it also to the genius of this same man, Foucault. It depends upon the same principles and is connected with the same series of facts as the other. But before proceeding to discuss this second experiment it will be well to consider these two tables, which have been taken from Galbraith and Houghton's *Astronomy*, because they show not only what the swinging pendulum should do if it behaves properly, but also what the gyroscope, the instrument used in the second experiment, should do if it behaves properly.

The first Table is called

Hourly Motion of Pendulum Plane.

Place	North Lat.	Observed motion per hour	Calculated motion per hour	Observer
Ceylon	6° 56′	1°·870	1°·815	Schaw and Lamprey.
New York	40 44	9·733	9·814	Loomis.
Providence, R.I.	40 49½	9·955	9·833	Carswell and Norton.
New Haven, Ct.	41 18½	9·970	9·929	
Geneva	46 12	10·522	10·856	Dufour and Wartman.
Paris	48 50	11·500	11·323	Foucault.
Bristol	51 27	11·788	11·763	Bunt.
Dublin	53 20	11·915	12·065	Galbraith and Houghton.
Aberdeen	57 9	12·700	12·636	Gerard.

The second is

Rotation of Earth deduced from Pendulum.

Place	Time of Rotation		
	h.	m.	s.
Colombo, Ceylon	23	14	20
New York	24	8	9
Providence, R.I.	23	38	29
New Haven, Ct.	23	50	7
Geneva	24	41	39
Paris	23	33	57
Bristol	23	53	2
Dublin	24	14	7
Aberdeen	23	48	49
Mean value	23	53	0

The pendulum plane is of course the plane in which the pendulum swings. The first column in Table 1 gives the place where the pendulum was set swinging, the second the latitude, the third the observed motion per hour, and the fourth the calculated motion. The table has been so drawn up that it begins with places nearest the earth's equator and passes gradually to others further away, going from Ceylon at 6° N. lat. to New York at 40° N. lat., New Haven at 41°, and ending with Aberdeen at 57°. At the first-named place it will be seen that the pendulum swings through less than 2° per hour, whilst at Aberdeen it swings through nearly 13°, which is an approximation, at least, to the statement I have made, that, since the rotation of the pendulum plane will be most rapid at either pole, the further from the equator we swing it the greater will be the number of degrees passed over per hour.

The gyroscope.

To return now to the gyroscope. We shall expect, if we succeed in imparting to it a rotation which is independent of and unaffected by the earth's rotation, that the angular change shown by it will be the same as that indicated by the pendulum, or, in other words, that the number of degrees passed over will be the same in both cases.

In the gyroscope, that portion which corresponds to the swinging part of the pendulum is the heavy disk seen in Fig. 28, to which a very rapid rotation can be imparted. This disk is mounted upon the horizontal circle shown in the figure, which circle in its turn is mounted in a vertical one suspended by a bundle of raw silk fibres which depend from the little screw shown at the top, Fig. 29, by means of which the whole system can be raised, so preventing the vertical circle from resting its whole weight upon the pivot below, the use of which is not so much to support the apparatus as to guide it in its movements.

Now in order that the rotation of the disk shall be uninfluenced by the motion of the earth a great number of precautions have to be taken. The first of these is to insure that the whole of the apparatus shall be perfectly free to rotate, and that, however much the silk fibres supporting the vertical circle may be screwed up in order that it may not rest its weight upon the pivot, its motion shall not be interfered with—that there shall be no twist in the thread.

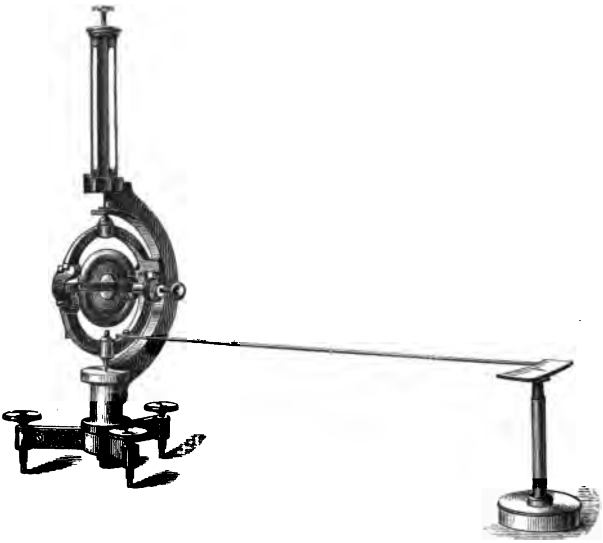

FIG. 29.—Gyroscope; general view.

This is the first precaution; and, when this has been done, a condition of things is obtained in which the apparatus is perfectly free to move round a vertical axis represented by the silk fibres prolonged. Then, having fulfilled this condition, the next matter of importance is to see that the disk is perfectly free to move on the horizontal axis. For this purpose the wheel which holds the two extremities of the axis of the rotating disk is armed with counterpoise weights (see Fig. 28), two in a horizontal plane, A A, and two in a vertical plane, of which one is seen at B.

Then the knife edges, C C, which are exactly in the plane of the centre of motion of the whole system, are made to rest on two steel plates mounted on a separate stand, in order to ascertain if the moving parts are perfectly balanced, the perfection of balance being determined by the slowness with which it oscillates up and down. But this is not all; it must not only be so adjusted by these weights, A A, that the ring shall remain horizontal, but it must be so perfectly balanced by the two weights, one of which is seen at B in Fig. 28, that if a considerable inclination be made from the horizontal it will be taken up equally on both sides. Finally, the instrument must be so adjusted that when the two delicate knife edges are placed on the two steel plates in the outer ring (see Fig. 28) the ring carrying the disk shall be perfectly free to move and have its centre of motion exactly identical with the centre of motion of the outer ring and of the disk itself. Then, when all these precautions have been taken, and the disk is set rotating with considerable velocity by means of a multiplying wheelwork train, we have, as far as the mechanics of the thing are concerned, an experiment just like the other, with this important difference, however, that, whereas the pendulum experiment always succeeds, much trouble is often experienced in experimenting with the gyroscope. But, when the multiplicity of the conditions necessary to the success of the experiment is considered, this is not surprising. If, however, all the conditions have been adhered to, the pointer with which the instrument is fitted (see Fig. 29) ought to move over the scale at exactly the same rate that the pendulum moves over the scale beneath it. But even supposing that the pointer of the gyroscope does move over the paper and in the right direction when the apparatus rotates one way, this is not enough. The demonstration of the validity of the result given by it is that an equivalent deviation is obtained when the apparatus is turned about in every possible direction. The first test of course is to rotate in the opposite way, then, if all the adjustments have been properly made, the deviation obtained will be the same in amount and direction as before, and it may be taken that the result obtained is one really due to the earth's rotation.

With this reference to the most important points connected with the gyroscope, we may bring our inquiries under this head to a close. So many men have worked with the instrument in so many lands, and under such rigid conditions, that there can be no doubt that the rotation of the earth is demonstrable by it, although certainly its verdict is not anything like so sharp, or so clear, or so easily obtained, as that given by the pendulum.

Our appeal to physics has at once put out of court the old view of the arrangement of the universe, which placed an immovable earth at its centre. How Copernicus was the first to point out that this old view was incorrect, and that it was the earth which moved, and how Galileo was persecuted because he, in times much less fortunate than our own, had the courage to say so—these are familiar points in the history of the discovery of the earth's rotation.

Study of the earth's rotation.

Having then demonstrated the existence of this particular movement of the earth, we must now proceed to a consideration of the rate, direction, and results of the movement—connect in fact the pendulum of Foucault with that of Huyghens.

Turn back to our two tables. They are not without interest at the present moment. In the first table, "Hourly Motion of Pendulum Plane," the observed motion of the pendulum plane per hour is connected with the latitude of the place at which it swings, varying as that varies; and therefore the observed motion in any latitude ought to give the same value for the earth's rotation, the closeness of which to the real value will at the same time be a measure of the accuracy of our pendulum observations.

Let us endeavour then to find out in what time the earth must rotate in order that the pendulum plane may vary (say) $1\frac{8}{10}^\circ$ per hour in Ceylon, $11\frac{9}{10}^\circ$ in Dublin, and so forth.

Taking our clock as being divided into twelve hours, each hour into sixty minutes, and each of these again into sixty seconds, it is found (see Table 2) that the value for Ceylon is 23h. 14m. 20s., and for Dublin 24h. 14m. 7s., the mean value of the observations at the various places mentioned in the table being 23h. 53m., so that according to that table the earth rotates on its axis in a few minutes less than twenty-four hours.

Now although such an approximation to the real value may suffice for the great mass of mankind, it is not an astronomical way of dealing with the question. We have seen the circumference of a circle divided first into degrees, then into ⅓ degrees, next into seconds, and finally into tenths of seconds; by the application of electrical principles, time has been even more finely divided, and the question naturally arises, Are there any means of determining the exact period of the earth's rotation?

There are means of doing this. In the last chapter occasion was taken to point out that the stars are infinitely removed from the earth; the stars being so infinitely distant, a slight change in their position will not be perceptible to an observer on the earth, and the place of a star to-day and its place to-morrow are the same so far as any parallactic change of position is concerned.

This being premised, it will be clear that, in order to get out the exact period of the earth's rotation, one only has to make an observation of any star on one particular day (such observation being of course made with a clock), and repeat the observation when the star is in the same position on the succeeding day. The time which elapses between the observations must be the time taken by the earth to make a complete rotation. But it will be asked, How are these observations made, and how is it known when the star *is* in the same position when the second observation is made?

The transit instrument and sidereal clock.

For this purpose a transit instrument is used (see Fig. 30). This differs from an ordinary telescope, being so mounted as to move only up and down, in the meridian of the

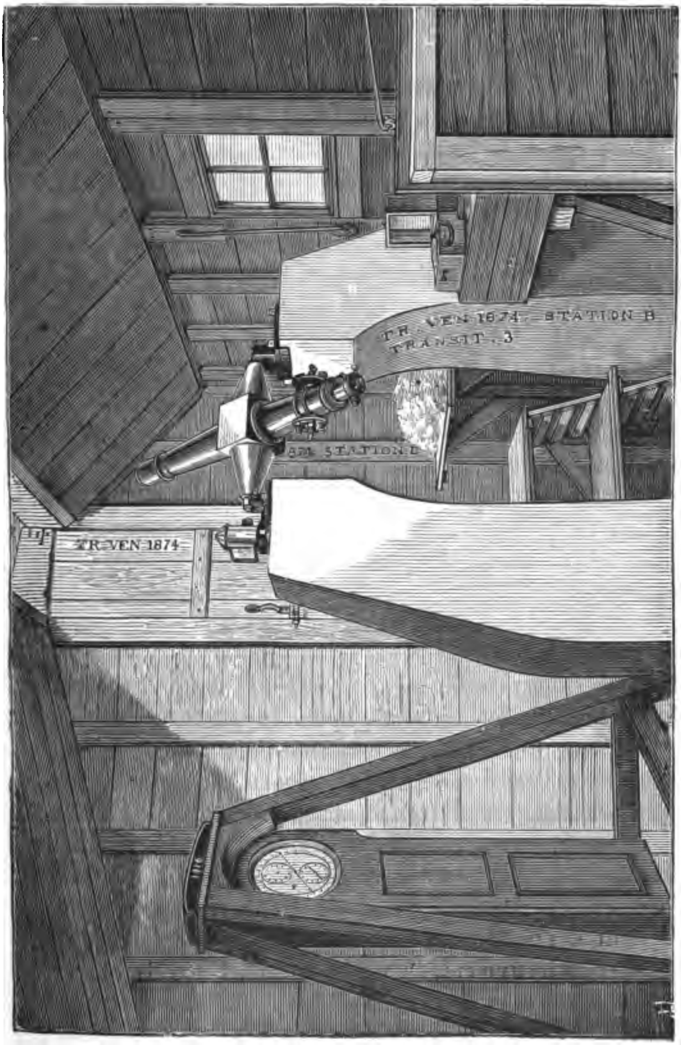

FIG. 30.—Transit instrument and clock.

place where it is used, and is armed not with simple cross wires, but with an odd number of parallel and equidistant vertical wires crossed by a double horizontal one. It is also usually provided with a circle to give declination. If from any part of the earth an observation be made on any particular star on one day, and then another observation is made on the same star when it is in the same position the next day, as has been said, the interval between the two observations must be the time taken by the earth to rotate once.

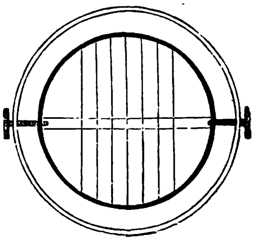

FIG. 31.—Wires in transit eyepiece.

By having such an arrangement as exists in the transit instrument, by which it can swing in the plane which contains the axis on which the earth turns, any star visible in the meridian of the place may be chosen for the observation. If, for instance, the instrument be pointed to the north pole star, the axis of the telescope will be nearly parallel to the axis of the earth. When the instrument is upright it points to the zenith.

In this instrument, as we have said, a star is observed when crossing the central wire of the instrument one day, and it is noted again when it crosses that wire on the succeeding day. But the observer does not limit his observation to the one central wire, in order to ascertain when the star is in the centre of the field. If he did so, he might miss his observation. That is why the simple cross wires have been replaced by a system of wires (see Fig. 31). As the star crosses the field of view, the observer, listening to the beats of the clock alongside, notes the time when it crosses each of the wires, and takes the mean of these observations, thus attaining to a much greater accuracy than if he had merely observed the transit over the central wire. With an ordinary clock it is found that a period, less by a few minutes than twenty-four hours, elapses between two successive transits.

In order to get an absolutely perfect measure of time, the clock may be so rated that it should not be any indeterminate number of hours, minutes, and seconds, but twenty-four hours exactly between the two transits of that star. With a clock thus arranged, the time at which a star crossed the central wire of the transit instrument would really give a most perfect method of determining that star's place in the heavens, because, if the earth's rotation is an equable one and takes place in a period which we choose to call twenty-four hours, then two stars 180° apart will be observed twelve hours after one another, four stars 90° apart will be observed six hours apart, and so on; and clocks like this, regulated to this star time, exist in our observatories, being called sidereal clocks, because the time they give, which is not quite familiar to everybody, is called sidereal time.

The apparent diurnal movements of the stars due to the earth's rotation.

Now let us consider our position on the earth with regard to the stars. This is a very interesting part of our subject, not only in its scientific aspect, but from the point of view of its usefulness, whether we wish to study the stars or define places on the earth's surface, the latter matter, however, being so intimately connected with astronomy proper that it is impossible to talk about the one without talking about the other.

Since we divide all circles into 360°, the circumference of the earth may be so divided, and the method in use of defining positions on the earth is to say of a place that its latitude is so much and its longitude is so much. Latitude begins at the equator with 0°, and terminates at the poles with 90°, being north latitude in the one case, and south latitude in the other. In the case of longitude, there is no such simple starting point, for whilst latitude is counted from the equator by everybody all over the world, longitude may commence at any point. In England we count longitude from the meridian of Greenwich. When the transit instrument at Greenwich is swept from the north point through the zenith to the south point it describes a half circle, which is called the meridian of Greenwich.

That is one point. Another point is this. Suppose the instrument to be set up not at Greenwich but at the north pole. Then the true horizon of the observer will be along the equator. Remove the instrument to the equator, and the true horizon will cut the poles. At a place in mid-latitude the true horizon would cut neither the pole nor the equator, but would be inclined to both (see Figs. 32, 33, and 34).

Then comes the important relationship between the latitude of the place and the altitude of the pole star above its horizon; supposing a star to occupy that position, the number of degrees this star—be it north or south—is above the horizon of the observer will be the number of

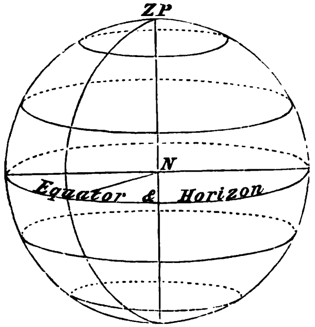

FIG. 32.—Showing that at a pole the true horizon is the equator.

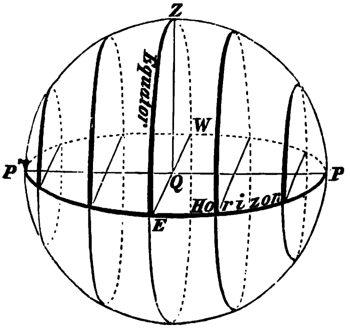

FIG. 33.—Showing that at the equator the poles lie in the horizon.

degrees of north or south latitude of the place where the observation is made. A place therefore in 10° N. lat. will have the north pole star at a height of 10° above its horizon.

There is a pretty bright star *near* the *north* pole, but not at it; but there is no bright star near the south pole.

So much for this part of our subject in extension of what has already been said in Chap. III. We must now leave it, because, interesting as it is, it refers to a branch of astronomy with which at present we have less to do than with the more physical one; but it was well that we should pause for a few moments to note the tremendous importance to mankind of that particular movement of the earth which we have been considering.

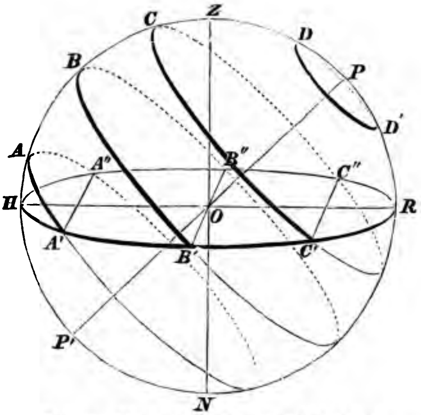

FIG. 34.—Horizon of a place in mid-latitude.

CHAPTER V.

THE EARTH'S REVOLUTION.

The apparent annual movements of the stars.

It will be clear from what has gone before that the daily movement of the stars is an apparent one due to the real movement of the earth in an exactly opposite direction, and that the stars in the heavens appear to rise in the east and set in the west, because the earth rotates from west to east. And now comes this question: The period of twenty-four hours which is so familiar, and which is divided roughly into day and night, has apparently two perfectly different sides to it. For a certain period the stars are not seen at all in consequence of a body, which we call the sun, flooding the earth's atmosphere with its own tremendous light. Why should this be? In giving an answer to this question it is enough to say that the sun is a star so close to us, and so entirely outshining the other and more distant stars which are seen in the skies, that they seem to be things of a different order altogether. But they are not things of a different order, the stars are very much like our sun, and the different appearance is simply the result of the fact that the one is a star very near to us, whilst the others are suns inconceivably remote. In considering this apparent daily movement of the stars, and taking the sun into consideration, the fact is soon arrived at that the stars have another apparent movement differing somewhat from that one with which up to the present time we have alone been engaged. It has been said, and it is so obvious that it might almost have been left unsaid, that as a rule the stars are not seen when the sun is visible, so that the question whether the sun moves or appears to move among the stars must be attacked in a rather indirect manner. An observer on that part of the earth's surface directly under the sun sees it as at midday. Under these conditions the stars are of course not seen by him, but if he waited twelve sidereal hours, until that portion of the earth which he inhabited was opposite the sun's place, the stars would be best visible, and by noticing whether those seen by him each night were the same, he would be able to determine whether or not the sun moved or appeared to move among them. In one position of the sun it occupies that constellation of stars known as the Bull. These stars cannot then be seen, because the intense brilliancy of the sun puts them out, but with the sun in this position the group of stars known as the Scorpion is seen opposite at midnight. Then at a later period the sun gets into the constellation called the Crab, and we see at midnight no longer the Scorpion group, but the group which is called the Goat. In this way it can be determined that the sun has an apparent movement among the stars, which is completed in a period which we call a year, at the end of which time the sun occupies the same position that it did a year previously, and the same group of stars is seen again in the south at midnight.

Not only, then, do the stars appear to make a complete revolution once a day, in consequence, as we have seen, of the earth's rotation, but once a year they also gradually change their apparent places, so that at the same hour each night different stars appear due south, thus indicating a movement of the sun among them.

These are due to a yearly revolution of the earth round the sun.

The same difficulty that was met with before is again encountered here; Is this movement of the sun among the stars a real or an apparent one? It is a question, however, which has been long since answered; and it can be very definitely stated, not only that the earth rotates on its axis in a period of twenty-four sidereal hours, but that it moves or revolves round the sun in a period which we call a year, and that it is this real movement which causes the apparent one of the sun among the stars. Let the reader take a top and spin it. Perhaps the top has a movement of progression as well as a movement of rotation, and it is in that way quite easy to see that the earth may rotate on its axis and revolve about the sun at one and the same time. And with a top of special construction its axis of rotation might be inclined so that its plane of rotation ceased to coincide with the plane of its motion of progression; still the two movements would go on, and in whatever position the top might be placed, its axis might be made to remain practically parallel to itself during its movements.

We may now, then, make the following statements:—*The earth revolves round the sun, and throughout the revolution the axis of rotation remains practically parallel to itself.* With regard to the latter part of this statement it may be added that if this were not so — if the axis of the earth were subject to perpetual change of direction—the declinations of the stars would also be subject to constant change.

Dr. Bradley's observations.

The demonstration of this movement of the earth round the sun depends upon physical considerations in exactly the same way as does the demonstration of the earth's movement of rotation, and to these considerations attention must now be turned. It will be found that we have now to do with an entirely different branch of physics from that which we drew upon when seeking for a proof of the rotation. The utilisation of its principles for the purposes of astronomy is due to Dr. Bradley, a former Astronomer-Royal. In the years 1726–8 he made a series of observations of stars, expecting certain results to flow from them. Instead, however, of getting the results for which he had looked, his observations gave him some which differed entirely from his predicted ones, and which he failed to understand. He found that the stars described ellipses in the course of a year instead of remaining exactly in the same apparent place. For such a thing as this to happen is a piece of good fortune for the scientific investigator; it sets him thinking and working, and frequently leads him to the discovery of some hitherto unknown physical law. It set Dr. Bradley thinking and working. Curious as it may seem, the observation which led him to a complete understanding of this subject was what he noted one day when a boat at anchor near the shore at Greenwich began to get under way in a stiffish breeze. The little boat had one of those short pennants on its mast, and Dr. Bradley noticed that, as soon as the boat began to move, the direction of the wind, as indicated by the movements of this pennant, changed. Before proceeding to consider the bearing which this fact, seemingly remote from astronomy, has upon star work, it may be advisable to take one or two simple illustrations, which will show what must have passed through Bradley's mind as the explanation of the strange unexpected movements of the stars was slowly growing within it.

Some illustrations and a possible explanation.

The first illustration which may be given is one due to Sir George Airy. Suppose that a vessel is passing a fort, and that a shot is fired from the fort at the moving vessel. The shot will travel in a straight line; but it is evident that since the ship is moving, if that shot really pierces both sides of the vessel, then a line joining the spot where the ball pierced the one side to the spot where it pierced the other side will not be square to the direction of the ship's motion. During the short time taken by the shot to pass from one side of the ship to the other, the vessel has moved through a certain small distance, and if the line joining the two shot-holes were alone considered, it might be inferred that the shot had come from a direction in advance of the true one. That is one illustration, the point of it being that the motion of the vessel seems to have given a new direction to the shot. Take another illustration, more familiar, and perhaps almost as clear. In this country frequent opportunities offer themselves of travelling in cabs or railway trains, with the rain falling on their closed windows. Every one must have noticed that at such times there is always a very curious slant in the apparent direction of the drops whilst the train or the cab is in motion; the rain seems to come from a point in front of us; we always seem to meet the rain. The fact is that a body in motion, and especially a body with the velocity of an express train, does not receive the rain under the same conditions as when it is at rest. The question of its velocity has to be taken into consideration. An experiment will show better what is meant.

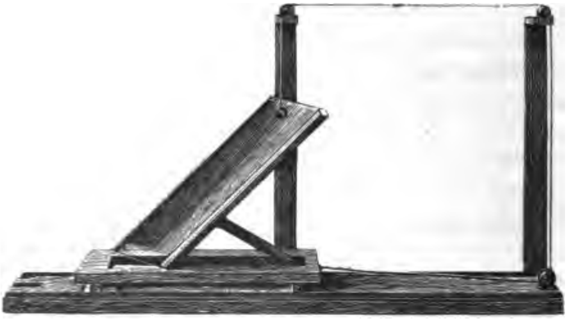

FIG. 35.—Model to illustrate the aberration of light. A square tube, with glass front and a slit along the centre of its upper side to allow the passage of a thread, is inclined at 45° and caused to run along a level track, while a weight suspended from a thread passing round three pulleys and attached at the other end to the front of the carriage is allowed to descend. In this figure the weight is at the commencement of its fall.

Imagine a weight supported by a thread (Fig. 35); the moment that thread is cut the weight falls in a straight line to the ground. If it be desired, therefore, to receive the falling weight in a tube at rest under the weight, and so to receive it that it shall not touch the sides of the tube as it passes through, the tube must be held in an upright position. Take another step, and suppose now that it is a question of causing the weight to fall through the tube whilst the tube itself is travelling at a certain rate, say at the velocity of the falling weight. It is perfectly obvious that this cannot be done by holding the tube in a perpendicular position, the tube must be inclined, and the angle of its inclination will vary with the varying relative velocities of tube and weight. The more quickly the weight falls the less inclined must the tube be to receive it. This not only supplies the explanation of the slant of the rain on the windows of the railway carriage, but it explains what is very much more important from an astronomical point of view. Consider Fig. 37 for a moment. Here A B represents the path of anything falling, and *a* C B

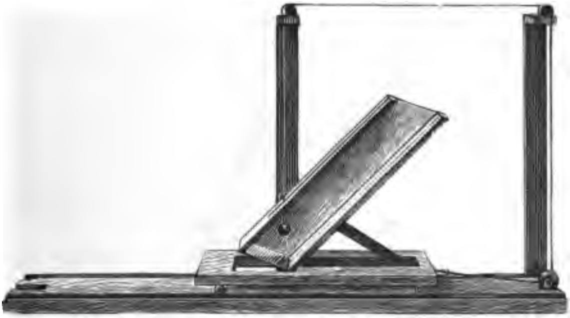

FIG. 36.—Same apparatus as preceding, with the weight near the end of its fall, but still in the centre of the tube.

the angle of the tube destined to receive it. It may be called the angle of slant, but the point is not that we give it any particular name, but that its relation to the velocity of fall is a very fixed and definite one. Accept it as such, and then connect it, not with the falling weight or with the slant of the rain, but with the velocity of the light coming to the earth from any star in the heavens, and the velocity of the earth in its orbit round the sun.

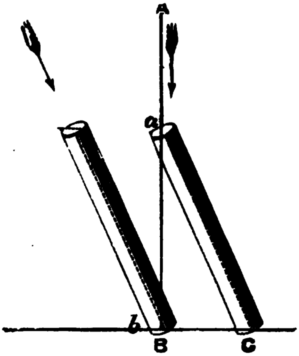

FIG. 37.—Diagram illustrating explanation of Bradley's observation.

We can now understand Dr. Bradley's explanation of his observation, the stars were always seen in advance of their real place because the light which came from them *took time* like the raindrops, and the telescope was carried by the earth which was moving like a train. Further, they appeared to move round a fixed point, because the telescope which observed them was carried round the sun each year.

Measurement of the velocity of light.

It may be said that two assumptions are here made, first that light has a velocity, and secondly that the earth does move round the sun. Consider, then, the first of these, the question of the velocity of light. In our day, with all the experimental methods and niceties which the labours of those who have gone before have placed at our disposal, this question of the velocity of light can be answered by what is called a laboratory experiment. The first real attempt to answer the question was made some years ago by a Frenchman, M. Fizeau. His method of observation was a beautifully simple one, and has turned out to be highly satisfactory in its results. All the essential parts of his apparatus are shown in Fig. 38. Light from a lamp was made

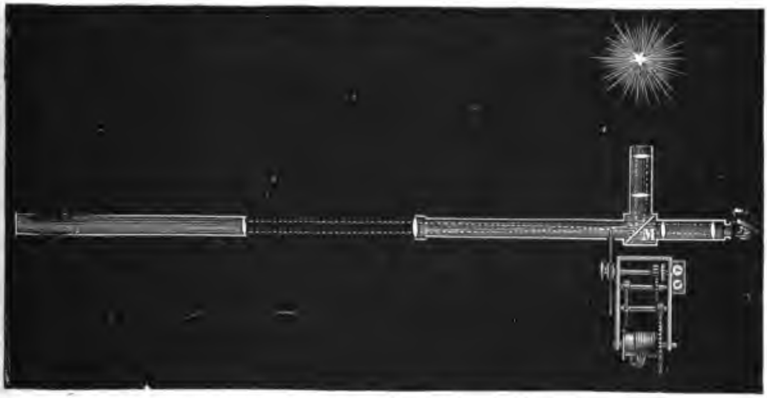

Fig. 38.—Fizeau's mode of determining the velocity of light.

to pass through a system of lenses and was brought to a focus after reflection from the front surface of a piece of plain glass. The light was then grasped by an object-glass and sent out in a parallel beam to a station distant about five miles. There it fell on another object-glass, which again brought it to a focus on a mirror at the end of this second telescope. Then having got the light to the second mirror, it was reflected on its path back again. When the reflected light returned, part of it was allowed to go through the plain glass mirror to the eyepiece seen at the end of the telescope

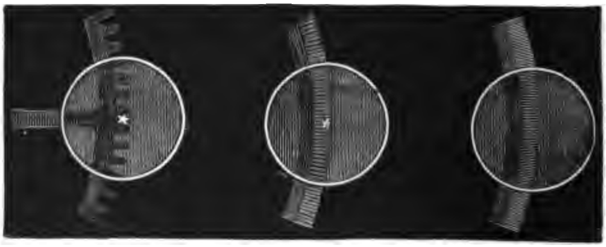

FIG. 39.—Fizeau's velocity of light apparatus. Appearance when the toothed whee is at rest, when it is in slow motion, and when its rotation is so rapid as to cause complete extinction of the light.

in Fig. 38. At the point where the rays crossed in the first telescope there was interposed the edge of a cogged wheel, to which a great velocity of rotation could be imparted by clockwork, and through the intervals between the teeth of which the light had to pass. Suppose first that the wheel is at rest. The lamp is lighted, and looking through the cogs of the wheel the observer sees the image of the lamp reflected back to him as a star of light from that distant mirror by means of the arrangement to which reference has been made.

Assume now that light occupies no time in travelling from the lamp to the first mirror, through the first telescope, across the space between the two telescopes, and back again after its reflection by the second mirror. Assume, in fact, that the velocity of light is infinite, then it is perfectly clear that an observer would keep on seeing that star of light whether the wheel remained at rest or were put in motion. But now assume that light does take a certain very small time to make the journey spoken of, and that the wheel can be turned with just such a velocity that when the light reaches it on its return it will meet, not an opening, but one of the cogs. Then the light would not be visible; it would find itself a cog behind, so that, if the velocity of the wheel and its distance from the mirror be known, the velocity of light can be measured in this way. Thus, while the wheel moves through the space of a cog, light travels twice the distance between the wheel and the mirror. That is the way in which Fizeau measured it, and he gave the velocity as being 190,000 miles per second.

It may be thought perhaps that this being the first attempt in a matter of this kind it was not very worthy of credit; but the similarity of the results which have been obtained in all such experiments proves that they are all very worthy of credit, and that this velocity must be accepted as established within narrow limits.

We come now to Foucault, the man to whose genius science owes the experimental proof of the earth's rotation, to which reference has already been made. He also attacked this question of the velocity of light. Going to work in quite a different way from Fizeau, he succeeded in enriching science with a method quite as reliable in its operation and as accurate in its results.

A pencil of light coming from a slit at S (see Fig. 40) impinges upon the plane mirror R, which is capable of turning round a vertical axis. This mirror reflects the light falling on its surface, and the action of the lens, L, causes an image to be formed on the surface of the concave mirror, M, the centre of which coincides with the axis at R. This concave mirror reflects the image backwards on its path to the slit. Foucault's arrangement, as has been said, was to have the mirror, R, made to rotate. If, therefore, R be turned about its axis while the light from the slit, S, is falling upon its surface, for so long as the light falls on the lens so long will the image of the slit be formed on the surface of the distant mirror. Similarly for so long as the reflected image falls upon the lens, so long will the image be reflected back to the slit. Now if the mirror were made to rotate rapidly, and light were infinite in its velocity, then once during a portion of the revolution, while the rays fall on any part of the mirror M, the light would be reflected back to the slit; but assume that light takes some very small fraction of time to travel over the space between the mirrors, it will be observed that the image will not be reflected back to the slit but will suffer a deflection in one direction or the other according as the mirror turns from left to right or from

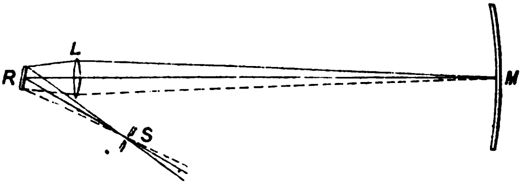

FIG. 40.—Foucault's arrangement for determining the velocity of light.

right to left, and, the velocity of the rotating mirror being known, the amount of this displacement will enable the velocity of light to be determined.

With two such different methods it might be supposed that the results obtained were very different. Not so, however; the velocity obtained by Fizeau was, as I have said, 190,000 miles per second, that by Foucault 185,000 per second.

It so happens that both these methods have been gone over quite recently, Fizeau's method by another Frenchman, M. Cornu, and Foucault's by Mr. Michelson, an officer in the American navy, and still later by Professor Newcomb.

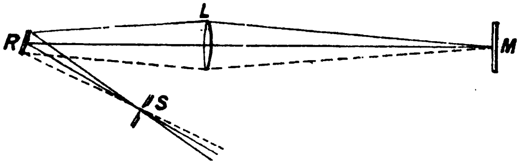

FIG. 41.—Michelson's variation of Foucault's experiment.

Mr. Michelson modified Foucault's method somewhat, the fault in which was that the displacement obtained was so extremely small, being but the fraction of a millimetre; and when it is remembered that the image is always more or less indistinct on account of atmospheric conditions and imperfection in the lenses and mirrors employed, it will be seen that it was difficult for Foucault to attain to any very great accuracy. Mr. Michelson therefore used an apparatus which would give him a greater deflection than that obtained by Foucault. As before, S (Fig. 41) was the slit, R the rotating mirror in the principal focus of the lens, but the distant mirror, instead of being concave, was a plane one, and the lens one of great focal length, for a reason that will appear immediately. This lens, in consequence of the smallness of its diameter in comparison with its great focal length, was not entirely convenient. In order that the displacement should be great, it is necessary that the distance between R and M, the distance from the revolving mirror to the slit, and the speed of rotation should be the greatest possible.

Unfortunately, the second condition clashes with the first,[1] for the distance from the revolving mirror to the slit, or the "radius," is the difference between the principal focus of the lens L and its conjugate focus for the mirror M, and the greater the distance the smaller the radius. Two methods were employed by Mr. Michelson in overcoming this difficulty: first, he had his lens of great focal length, 150 feet, and he placed the revolving mirror, not at the principal focus, but fifteen feet within it. He thus managed to get a distance between the mirrors of 2,000 feet with a radius of thirty feet, and his mirror made 256 revolutions per second. He then obtained a deflection of 133 millimetres, that being about 200 times greater than the deflection obtained by Foucault. This deflection he measured to within three or four hundredths of a millimetre in each observation.

Professor Newcomb has still more recently executed a series of similar experiments with such elaboration that the resulting velocity for light, 186,328 miles a second, can scarcely be more than twenty miles a second wrong either way.

We are therefore justified in saying, as the result of these experiments of Fizeau and Cornu, Foucault, Michelson and

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[1] For full details of Michelson's experiments, see *Nature*, vol. xxi. p. 94 *et seq.*

Newcomb, that light has a velocity of some 186,000 miles per second.

Statement of the phenomena actually observed.

Light then does not travel infinitely fast, and this being so, if the earth moves in an ellipse in a year, the stars must seem to describe ellipses in the same time. We have seen that they do, and if that be so, then the statement that the earth revolves about the sun must be true. In Fig. 42, *a*, *b*, *c*, *d*, represent the earth in different parts of its orbit around the sun; the contention is that if there be this revolution of the earth round the sun, and if light really travels with anything short of an infinite velocity, then the position of a star must change, for the reason that the telescope of the astronomer must always be pointed in advance of the star to catch its light in the same way that to catch the falling weight we had to incline the tube in the direction of its motion. If the earth did not revolve round the sun the stars would not describe ellipses.

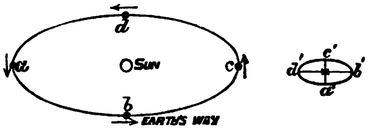

FIG. 42.—Annual change of a star's position, due to aberration: *a b c d*, the earth, in different parts of its orbit: *a' b' c' d'* the corresponding aberration places of the star, varying from the true place in the direction of the earth's motion at the time.

When an observation is made on any star in the heavens, then the telescope of the astronomer must therefore be pointed in advance of the star to catch its light, and taking, as in the diagram, four different points in the earth's orbit, it is obvious that the telescope at these four different points must be pointed in four different directions with regard to the star. For instance, if we take a point at *c*, where the earth is travelling in the direction of the arrow, and the point at which the star would be seen if the earth were at rest, or the velocity of light were infinite, be indicated by the star in the figure, then *c*′ is the direction in which the star would be seen, and in which the astronomer's telescope must be pointed to catch its light. Similarly with the earth at *d* the telescope must be pointed to *d*′, and so with the earth at *a* we must have it pointing towards *a*′.

Here is the explanation of the strange anomaly which puzzled Dr. Bradley in the year 1728. This fact of aberration, then, is a real thing. It has been said that the angle at which the tube had to be inclined to receive the weight depended upon their respective velocities, that the faster the tube travelled, the greater must be its inclination from the vertical, and therefore the greater the angle of inclination, the greater the earth's velocity with reference to the velocity of light must be. In the case of the majority of the stars what we get is an ellipse, and in an ellipse we have certain differences which have to be taken into account, the last difference of all being that an infinitely elongated ellipse is a straight line, and it is found that from one particular point of the heavens where, in consequence of this aberrational motion, the orbits of the stars round their mean places are almost circular, we at last get to a point where the motion is simply an oscillation of the star backwards and forwards to and from its mean place; we are dealing, in fact, with that projection of the ellipse which takes the form of a straight line. When we deal with an ellipse we no longer talk of the radius, but of the semi-axis major, which is half the greatest length. The angle of aberration of which I have spoken only amounts to 20″·492, but though small, it is quite enough to prove that the earth does revolve, and that consequently the sun is the centre of the system to which the earth belongs, while it further tells us that the movement of the earth is slow compared with that of light.

How the aberration constant enables us to determine the distance of the sun.

Now in concluding this chapter, in order to show the importance of physical inquiries in this matter, there is another statement which must be made. If we consider this aberration question fully, we find in it what is perhaps the most perfect way of determining the distance of the sun from the earth, and it will be seen that it is perfectly simple, so simple in fact, that the wonder is that more attention has not been given to it in our text-books. We have first the fact that the inclination of the tube depends upon the relative velocities of the tube and falling body, and in the case we are considering it will of course depend upon the relative velocities of the earth in its orbit and of the light radiated from a star. Knowing this latter to be somewhere about 186,000 miles per second, and the aberration angle to be 20″ and something, we can get the relation of the earth's motion to the velocity of light and it comes out to be about 1 to 10,089, that is, light moves 10,089 times faster than the earth travels round the sun.

Now we know that the earth completes a revolution round the sun in 365¼ days. If it travelled with the velocity of light it would complete a revolution in 52m. 8·5s. which is the 1/10,098th part of a year.

Again, we may say, and this is only a rough statement, that the radius of a circle is 1/6 of its circumference, so that if it takes the earth fifty-two minutes to go round a circumference, or, as we call it, its orbit, it would take 1/6 of that time to go along the radius if it travelled with the velocity of light; it would therefore take 8m. 18s. But this radius is the distance of the earth from the sun, and having this time 8m. 18s., we have only to multiply the velocity of light per second, by that, and we get 92,628,000 miles as the distance of the earth from the sun.

CHAPTER VI.

CONDITIONS OF REVOLUTION.

Form of the orbit.

We last appealed to those branches of physical science which are connected with the determination of the velocity of light, in order to see whether we could get any help in that direction on a most interesting question, a question which, like another to which attention has been drawn, might have been considered as an open one, unless one had gone beyond the range of ordinary astronomical observation with regard to it. It has now been seen that by investigating the facts connected with the velocity of light; first, that we could determine that velocity by two different methods with a wonderful agreement between them; and secondly, that, by taking the velocity of light and dealing with it in the way we then did, a perfect demonstration was obtained of the fact that the earth revolves in an orbit round the sun. It was further seen that using this velocity of light, and also this fact of the earth's revolution which it enabled us to demonstrate, we were able to say that the distance of the earth from the sun was, roughly speaking, 92½ millions of miles.

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We will now go more into detail with regard to the precise form of the earth's orbit, and consider some of the conditions under which the earth's movement in that orbit takes place. In proceeding to do this let us first suppose the orbit of the earth to be in the form of a circle with the sun in its centre, then it is perfectly clear that the earth will always be at exactly the same distance from the sun, and that consequently the sun as seen from the earth will always appear of the same size; but on the other hand if the earth does not move in a truly circular orbit round the sun, then, unless she moves with great irregularity—and we shall see subsequently that she does not—the only other possible course for her to take is an elliptical one, because if she took an orbit of any other form—that of a parabola or an hyperbola for instance—she would not revolve about the sun at all, she would not have a succession of years each of 365¼ days' duration, but one year, a year of infinite length; she would in fact go off at a tangent into infinite space.

Let us then consider what will happen if the earth instead of moving in a circular, travels in an elliptical, orbit, with the sun in one of its foci, and not in the centre of figure; then it is perfectly clear that the distance of the earth from the sun will vary, that she is nearer the sun at some points of her orbit than at others. So much for supposition. Let us consider the facts. We know that it is the duty of the astronomers at Greenwich to make daily observations, when possible, of the transit of the sun, by means of one of those transit instruments to which reference has been made. Now if the sun, as seen from the earth, had always the same apparent diameter, it is obvious it would always take exactly the same time to cross the central wire of the transit instrument; but when we turn to the record of the observations made at Greenwich we find this:—Take the year 1878. On January 9 in that year the apparent diameter of the sun was 33′ 33″·50 of arc, whereas on July 13 of the same year it was 31′ 30″·24; the apparent diameter was less, so that if these observations are to be depended on—and I know of none better—we were nearer the sun in January, 1878, than we were in July. If that be so, then there should be two intermediate points when the diameter of the sun was the same, with an interval of six months between them. This is what was observed on two such dates in this same year, on April 5 an apparent diameter of 31′ 58″·16, and on October 5 an apparent diameter of 32′ 5″·17. In this latter case we have a difference only of 7″·01; in the former case a difference of over 2′, so that the Greenwich observations quite justify the supposition that the earth moves not in a circle, but in an ellipse; because, the greater the distance of the sun from the earth, the smaller it must appear. While we

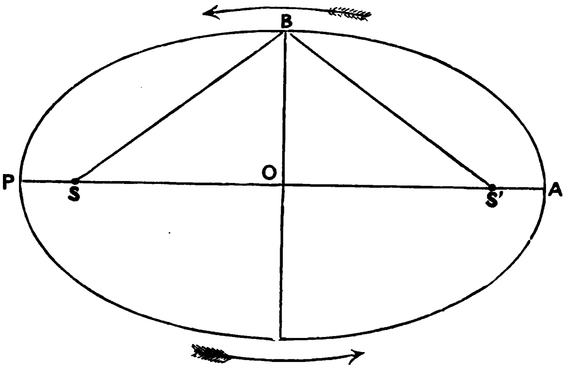

FIG. 43.

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are on this subject of the ellipticity of the earth's orbit, I am anxious to draw attention to two diagrams, so that the matter may be as clear as possible. Let us consider the diagram, Fig. 43. We have drawn there an ellipse, and the earth is assumed to move in the direction of the arrow round the sun placed in one of its foci, S. A similar ellipse may be easily drawn thus:—Fix two pins in a piece of paper at the foci S and S′, pass a loop of thread over them, and with a pencil trace out the curve by travelling round the pins, keeping the loop stretched all the time.

The line A P is called the major axis, and A O or O P the *semi-axis major.* O B is called the *semi-axis minor.* The ratio of O S to O A is called the *eccentricity*, and is usually represented by *e.*

Perihelion and aphelion points.

Now by the construction of an ellipse we know that S B, which represents the mean distance between the earth and the sun, is exactly the same as the distance A O or P O, the semi-axis major of the ellipse; for S B + S′B + S S′, or 2 S B + S S′, is the length of the string, as is also S P + S′P + S S′, or S P + S A + S S′, or 2 O A + S S′, and therefore S B = O A. O A is the mean distance because it is as much greater than the smallest distance, S P, as it is smaller than the greatest distance, S A. When the distance O S is very large as compared with O A, then the ellipse is a very flattened one, and the shorter the distance O S as compared with O A the less flattened will be the ellipse and the more nearly will it approach a circle. It will now be clear why the two points are marked A and P, for if S be taken to represent the focus of an ellipse actually occupied by the sun, the point P will represent the place occupied by the earth when it is nearest the sun, which is called by a Greek word, "perihelion," whilst the other point A will mark that point in the orbit of the earth when it is farthest removed from the sun, this being called by another Greek word, "aphelion." This aphelion distance SA is equal to the mean distance OA *plus* OA multiplied by the eccentricity; for $SA = OA + OS$, and $OS = e \times OA$, therefore $SA = OA + (e \times SA)$. Similarly the perihelion distance of the earth from the sun is equal to the mean distance OA minus OA multiplied by the eccentricity. These statements are general with regard to ellipses, and in order to make the point quite clear, we have shown them on the very flattened ellipse of Fig. 43, but the true form of the earth's orbit very nearly approaches a circle. If we want to find the greatest distance and the least distance of the earth from the sun at the opposite points of the orbit, we take the best value we can get of the mean distance SB, or OA, which is the same thing, and it is found that the eccentricity comes out about ·0167, or the mean distance multiplied by the eccentricity is about 1½ million of miles. The greatest distance of the earth is therefore less than 94½ millions, whilst its distance at perihelion is a little more than 91¼. So much then for the facts with regard to the varying distances of the earth from the sun at different periods of the year.

The earth moves with varying speed.

The next point is this: if the earth moves in this elliptic path round the sun, does she always move with the same

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velocity, does she go more quickly at some times than at others, or does she travel always with a steady, constant pace? Now here again the question can easily be answered by an appeal to the useful transit instrument. Our sidereal clock gives us a method of determining the interval, true to the hundredth part of a second, between one transit of the sun over the central wire of the instrument and another, and so enables us to determine the number of degrees, minutes, seconds, tenths of seconds, and hundredths of seconds of arc passed over by the sun in that time, twenty-four hours of time corresponding to 360 degrees of arc. If the earth, therefore, in her revolution round the sun moves with an equal unchanging motion, then it is clear that the number of degrees, minutes, and seconds of arc passed over in any given time will be always the same. Let us again consider the facts according to the Greenwich record. On December 27, 1877, the transit of the sun's centre occurred at 18h.

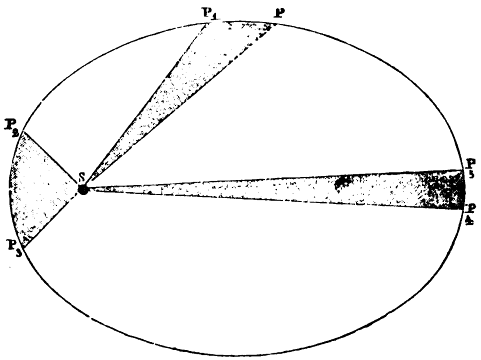

FIG. 44.—Diagram illustrating Kepler's second law.

25m. 44·9s. sidereal time, but on the day before it took place at 18h. 21m. 18·5s. If this second quantity be subtracted from the first, the difference comes out as 4m. 26·4s., the amount of arc passed over by the earth in that interval therefore being 1° 6' 36″. Now on June 29 of the same year we get 0h. 33m. 51·7s., whereas on the 28th the time was 0h, 29m. 43·3s., a difference of 4m. 8·4s. It is thus obvious that the motion of the earth is not uniform, and that being so, the question arises, Is this want of uniformity constant, or is it irregular? Is there, in short, any law governing it? It will be seen that there is a most perfect law about it; that when the sun looks biggest, that is to say, when we are nearest the sun, the earth moves most quickly, and that when the sun looks smallest from the earth, when the earth is at its greatest distance from the sun, it moves with its least velocity. This fact brings us face to face with a most fundamental law of astronomy—that law which is known as the second law of Kepler. This can be gathered from Fig. 44. Here S represents the sun in one focus of the ellipse representing the orbit of the earth, and we have P, P^1, P^2, P^3, P^4, and P^5 representing different positions of the earth at different times of the year, the distance between these points P, P^1, P^2 and P^3, and P^4 and P^5 representing the portions of the orbit passed over by the earth in equal intervals of time. This law is known as the Law of Areas. It states that in equal intervals of time the radius vector or line joining the earth and sun passes over equal areas in its revolution. Thus the area of the triangle S P P^1 is equal to the area of the triangle S P^2 P^3, and is also equal to the area of the triangle S P^4 P^5, and these areas of the orbit are passed over by the radius vector in equal intervals of time. When the earth is nearest to the sun she travels most quickly; when she is at her greatest distance from the sun she travels most slowly; and thus she keeps the figures inclosed by the radii vectores always of equal area during equal times. Let us be quite clear on this point: the law is not that the earth moves through equal distances in equal times, but that the areas of the spaces swept over by the radius vector are the same for equal intervals of time.

We come then to this: that the earth moves round the sun; that she moves in an ellipse; that she moves unequally, that is to say, with different velocities at different times, but that these different velocities are bound together by a well-defined and well-recognised law.

The plane of the ecliptic.

Now comes another question connected with this movement of the earth round the sun. When the movement of the earth on its axis was being discussed, it was pointed out that observations made by the transit instrument gave ample evidence that the movement was a perfectly equable one, and of such a nature that the axis of movement remained always practically parallel to itself. Attention must now again be turned to the axis of rotation. Let us take the earth in any part of its orbit, then the question is this: Is the plane of the earth's motion round the sun, or, as it must now be called, the *plane of the ecliptic*, identical with the plane of the earth's motion of rotation? That is to say, if the sun and earth were floating half immersed in an ocean of infinite extent, whilst the latter was performing its orbital motion, would its axis of rotation be at right angles to the surface of the ocean in which it swam? Suppose we had a globe to represent the earth, and on it a model of a transit instrument were placed in the direction it is pointed at Greenwich when the sun is being observed. Then if the axis of the earth were really vertical the instrument would always be at right angles to it, or practically so, for sun observations. Further, if the globe were turned round to represent one rotation of the earth, then if the axis on which it turned were really perpendicular, the sun's declination would remain unchanged, and its polar distance would always be 90°. Now let us refer to the Greenwich observations of the north polar distance (see p. 58) of the sun.

°
On March 16 N.P.D. was 91·34
„ 22 „ 89·12
June 22 „ 66

That is to say, the observers at Greenwich in going from March to June had to alter the inclination of their instrument, in consequence of this variation in the N.P.D. of the sun, to the extent of the difference between 90° and 66°. On September 21 of the same year the N.P.D. was 90°, but on December 17 instead of being 90°, or 66°, it was 113°·24. How can these facts be explained? Suppose we had a lighted lantern to represent the sun, and round it four globes were placed, with their axes vertical, to represent the earth in four different positions in its orbit. It will be obvious that if we bring the light of the lamp in succession upon the four globes with the axes in each thus vertical, then the zenith distance of the sun, represented by the lamp, would be the same in each case. That is the sun would always be in the zenith of observers supposed to be on the equator. In this position of the globes we get the boundary of light and darkness at the poles, and the line joining the centres of earth and sun will give us the zenith distance of the latter.

The axis of rotation inclined to the plane of the ecliptic.

Now assume a different state of things, that the axis of the earth is not vertical but is inclined to the plane of the ecliptic. In that case its spin of course would not be at right angles to this plane. If the four globes with their axes all parallel and in this new position were then illuminated in succession, it would be found that the presentation of Greenwich to the sun would be vastly different at the four different positions. In the first, if it were placed

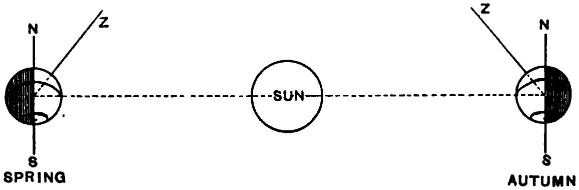

FIG. 45.—Diagram showing the equality of the sun's zenith distance at the two equinoxes. N, north pole of the earth; S, south pole; Z, zenith of Greenwich.

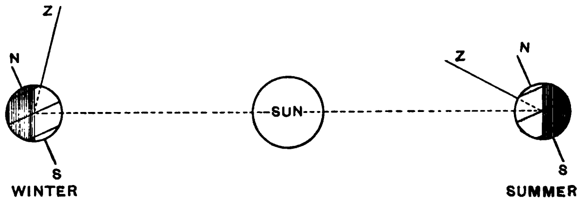

FIG. 46.—Diagram showing the variation of the sun's zenith distance at the two solstices. N, north pole of the earth; S, south pole; Z, zenith of Greenwich.

in the proper part of the orbit, we should get Greenwich, not turned fully to the sun, but still well in his rays. In the second one we should find the vertical at Greenwich pointing very much more to the sun than before, when the axis was vertical. In the third globe the conditions would be about the same as in the first, while in the fourth the line which points towards the zenith at Greenwich, instead of being turned almost directly to the sun, would be turned most away from it. This fourth position is that in which the zenith distance, and therefore the N.P.D., was greatest, *i.e.* when it was 113°. The second represents the position of the earth when it was the least possible, whilst the first and third positions would occur when the N.P.D. of the

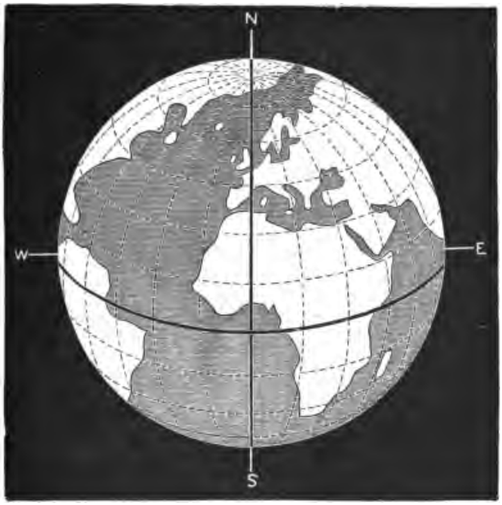

FIG. 47.—The earth, as seen from the sun at the summer solstice (noon at London).

sun was neither great nor small, but midway between the two extremes. These facts will be made clearer by the accompanying woodcuts, in which the globes are shown in four different positions. Fig. 45 represents cases 1 and 3, and Fig. 46 cases 2 and 4. In Figs. 47 and 48 these facts are shown in different ways: Fig. 47 represents the aspect of the earth as seen from the sun at the summer solstice, when it will be seen that England is seen to lie near to the centre of the hemisphere; while in Fig. 48, representing the conditions at the winter solstice, England is so near the edge that it cannot be properly represented. This experiment then will enable us to go further, and to say that the plane of the earth's equator, and therefore of the earth's

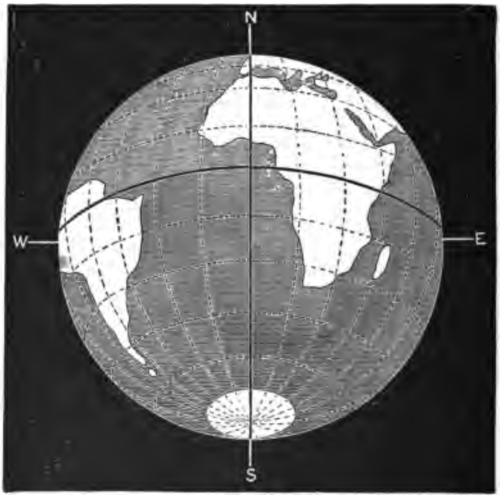

FIG. 48.—The earth, as seen from the sun at the winter solstice (noon at London).

spin, is not parallel to the plane of the ecliptic, but is inclined to it at an angle represented by the difference between 90° and 66°, or 90° and 113°; that is to say, the angle between these two planes, that of the earth's rotation and that of its revolution, is something like 23½°. It follows, therefore, that the earth's axis is inclined at 66½° to the ecliptic.

Nodes.

In the non-coincidence of these two planes we have one of the most fundamental points in astronomy, for the reason that what Greenwich is to earth measurement the point of intersection of these two planes is to heaven measurement. The result of this inclination of these two planes is that at one particular point in its course round the sun the equatorial plane of the earth seems to plunge below the plane of the ecliptic, whilst at another and an opposite point it seems to come up from below that plane.

These two points are known as the nodes of the orbit, the ascending node at that point where the earth comes up from below, the descending node when it is plunging down from above. It will be remembered that when the question of terrestrial longitude was occupying our attention it was pointed out that it might begin anywhere: we begin at Greenwich, the French prefer Paris, the Germans Berlin, and so on. With regard to celestial longitude, although it also might begin anywhere, yet there is a general agreement among astronomers that the right ascension of stars shall be counted from the ascending node, or, as it is otherwise called, the first point of Aries, where we get one intersection of the earth's plane of rotation with the ecliptic plane of revolution. That is the start-point not only of right ascension for the stars, but of celestial longitude, because it is necessary that we should have a means of stating the positions of stars, not only with reference to the plane of the earth's rotation, but with reference to the plane of the ecliptic itself, and the number of degrees which a heavenly body is observed above or below that plane (such degrees being called degrees of celestial latitude) is required to be known in order to determine absolutely the position of any star. Thus we have the following co-ordinates, or means of determining the position of a heavenly body.

With regard to the plane of rotation (*equatorial plane*):

Right ascension = distance from the first point of Aries.
Declination = distance N. or S. of the plane.

With regard to the plane of revolution (*plane of ecliptic*):

Longitude = distance from the first point of Aries.
Latitude = distance N. or S. of the plane.

With the transit instrument and the sidereal clock the precise angle of intersection of these planes has been determined in the way already described, but it is necessary to know also the precise point in the orbit at which the intersection takes place, before we can use either our transit instrument or our clock for the determination of the precise position of a heavenly body.

The first point of Aries.

And now that so much has been said, we can go further with regard to our sidereal clock, and state that it shows oh. om. os. when the first point of Aries is exactly on the central wire of the transit instrument, and that it will come back to that time, oh. om. os., after an interval of twenty-four hours of sidereal or star time, and it is obvious that we have at that point the most convenient starting point both for the right ascension of stars as determined by a sidereal clock, and the longitude of stars, if we choose to define their positions with reference to the ecliptic plane, instead of with reference to the plane of the earth's rotation. It is curious how in dealing with these matters we find that phenomena apparently the most diverse are really bound up in a most intimate connection with each other. In further considering the subject it will be seen that not only do we get these precious start-points from these considerations, but that they bring before us questions of the greatest interest and value to all earth-dwellers, questions that enable us accurately to study not only time as applied to the dealing out of our days and nights, as applied to those changes which take place during the year, and as applied to those changes which affect the years themselves, but as applied to those yet greater changes which have probably been going on in this planet of ours for very many millions of years.

CHAPTER VII.

RESULTS OF ROTATION AND REVOLUTION.

Day and night.

We have now to consider some of the results of these Movements of the Earth—first round its own axis, its rotation; then round the sun, its revolution—which we have been considering, results to which of course a general interest attaches, and which there will be no difficulty in showing are of very great importance to us. Occasion was taken to point out that the different appearances presented by the sun and the stars was simply due to the fact that the sun was very near to us whilst the stars were very distant, the one, a sun which happens to be near to us, the others, also suns, but happening to be very far removed from us. Now suppose we have a globe in which we have an electric light, to represent the sun, and a little globe to represent the earth, then it will be obvious that that part of the earth which is turned towards the lamp will be bathed in light, while that half which is turned from it will be in darkness, being, so to speak, only under the light of the distant stars. This shows us the reason for that great difference which we call day and night, and we can quite understand how it is that we get the apparent rise of the sun which occurs when the part of the globe on which we live is carried from the darkness into the light, and sunset which of course occurs when the globe is being carried by its rotation from the light into the darkness. This phenomenon of day and night is thus one of the most obvious results of the rotatory movement of the earth, and one which might have been dismissed in two words had we so chosen, but we will dwell upon it for a few moments, because this fundamental difference between day and night furnishes us with a reason why we should discard that sidereal time to which up to the present reference has alone been made.

Sun time.

Fig. 49 will show how it is that under the circumstances in which we thus find ourselves, a new kind of time must take the place of sidereal time. In this diagram we have the earth represented at two positions in its orbit, 1 and 2. It travels in this orbit in the direction of the arrows, rotating on its axis the while in the direction also indicated by arrows. Now let us consider the start-point 1, and suppose that when the earth occupies this position a particular star is on the meridian at midnight. The earth it will be remembered rotates in twenty-four sidereal hours; it will therefore take twelve hours to turn half round, so that if we consider the sun to be directly opposite the star which is south at midnight it is obvious that they are twelve hours apart. Now consider the earth at position 2. Then remembering this fundamental fact, that the distance of the stars is so enormous that a string stretched from the observer to the star at one point of the earth's orbit would be practically parallel to a string stretched to the same star from any other part of the orbit; it is obvious that the star will have the same right ascension in both positions of the earth, and the line pointing to the star will be practically in the same direction. But the sun will no longer lie along the prolongation of the line joining earth and star as it did at 1, for in consequence of the earth's revolution round the sun we shall get a gradually increasing angle as the earth in its orbital course gets farther and farther from its initial position at 1.

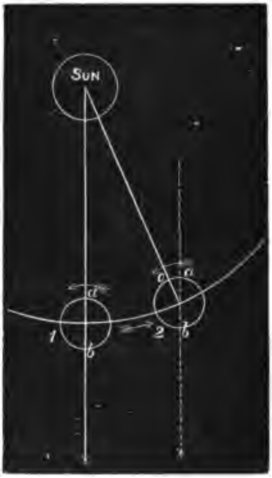

FIG. 49.—Diagram showing how the difference between the lengths of the sidereal and mean day arises.

Now it is obvious if we are going to have our time regulated by the sun instead of by the stars—and that is what we must do for the purposes of civil life—we shall have to arrange our clock so that when we pass from 1 to 2 it must, if it showed 12 o'clock when the sun was due south in the former position, show 12 o'clock also when the sun is due south in the latter position. If this be so, and we have this angle made by the line joining sun and earth and star, we shall have to make our sun-clock go more slowly than our sidereal clock, for the reason that the sidereal clock will have gone round once in less time than the earth will have taken to get round to the same place with regard to the sun. But if we choose, and we do choose, to say that we will have twenty-four hours from sun-southing to sun-southing, then these twenty-four hours, and necessarily also their minutes and seconds, will be longer than the hours, minutes, and seconds of sidereal time. Let us take another illustration. Consider the case of the earth in three different positions, represented by three globes round a central lamp. Then suppose that in each of these globes a wire is put to represent the direction in which the transit instrument points at Greenwich when the same star is observed at three consecutive intervals of twenty-four hours of sidereal time. These three wires should therefore be placed parallel to each other. Now let us take the electric lamp to represent the sun, then we shall find that, when the transit instrument on each of the earths is brought round to point at the sun, the three wires which represent the instruments will not be parallel to each other but at some angle.

Effect of unequal motion.

At first sight it might seem to be perfectly clear that we could easily get a sun-time to replace the star-time, but unfortunately when we go a little deeper into it we find as we often do in other cases, that it is not quite so easy—and for two reasons. We found, it will be remembered, when we came to consider the form of the earth's orbit, that it was not quite circular, that it was in fact what is called an ellipse, and that the radius vector, *i.e.* the imaginary line joining the centres of the sun and earth did not sweep through equal *arcs* in equal times but through equal *areas*, so that, if we want to invent a clock which will show twenty-four hours from the time of sun-southing one day to the time of sun-southing the next, that clock will require to be regulated differently for different parts of the year, because the greater or less part of its orbit moved over by the earth in a day or different parts of the year will cause a greater or less angle between the lines joining sun, earth, and star.

That I hope is clear. Thus then there is good reason why this arrangement of having a sun-time from noon to noon will not work. We should have to regulate our clock for every day in the year, or rather for every two opposite days.

Effect of inclination of fundamental planes.

But there is another matter. We are now in full presence of the fact that the equator of the earth is inclined at an angle of about 23½° to the plane of the ecliptic. Fig. 50 will perhaps enable us to understand this matter more easily. Let the horizontal lines represent the plane of the equator and the inclined lines the plane of the ecliptic. Now our clock and all measurements of time must depend upon the earth's rotation, the plane of which always remains parallel to itself, and we have seen that our start-point for celestial longitude depended upon the fact that at a certain point in its revolution the earth passed through a node, and that the node at which the sun with its apparent motion crossed the equator northward was called the ascending node. In the diagram this is represented by ♈ in the upper figure, and the descending node is indicated by ♎ in the lower figure. It will be seen that if we have equal intervals along the ecliptic the motion along the equator is represented by bases of successive triangles, of which the hypothenuses lie along the ecliptic. Now the hypothenuse must be greater than the base, so that we have at the ascending node the motion of a body along the ecliptic represented only by the base of a triangle of which the motion itself represents the hypothenuse; and the same thing happens in the opposite manner at the descending

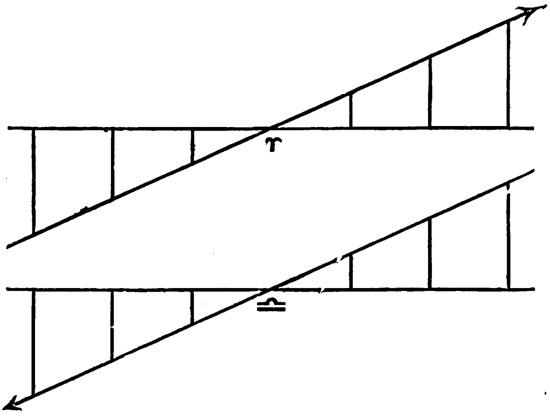

Fig. 50.—Diagram showing now the sun's apparent motion along the inclined lines representing the ecliptic in the direction indicated by the arrow-heads is represented by a smaller amount when referred to the earth's equator (the horizontal lines in the figure) at the spring (♈) and autumn (♎) equinoxes.

node. Next, if we take the other intermediate positions at the solstices shown in Fig. 51, the motion will be for a short time at all events parallel, and motion along the ecliptic will be represented by an equal amount along the equator.

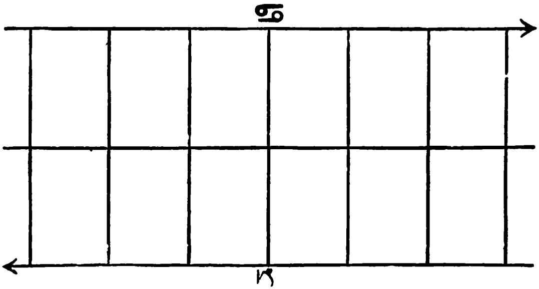

FIG. 51.—Diagram showing how the sun's apparent motion along the ecliptic, now parallel with the earth's equator (the central line of the figure) at the summer (♋) and winter (♑) solstices, is represented by equal intervals along the equator.

Equation of time.

These then are the difficulties we have to face when we come to fix our sun-time, first, the unequal velocity of the earth round the sun; and secondly, those variations which are brought about by the fact that the two motions of the earth—its axial rotation and yearly revolution—take place in different planes. How are these difficulties got over? They are got over by pretending a sun, as a child would say. Astronomers pretend that there is a sun moving along the equator, or, in other words, they imagine that the earth's movement of revolution takes place in the same plane as its movement of rotation. It is further supposed that this imaginary sun travels at precisely that rate which it would have if the

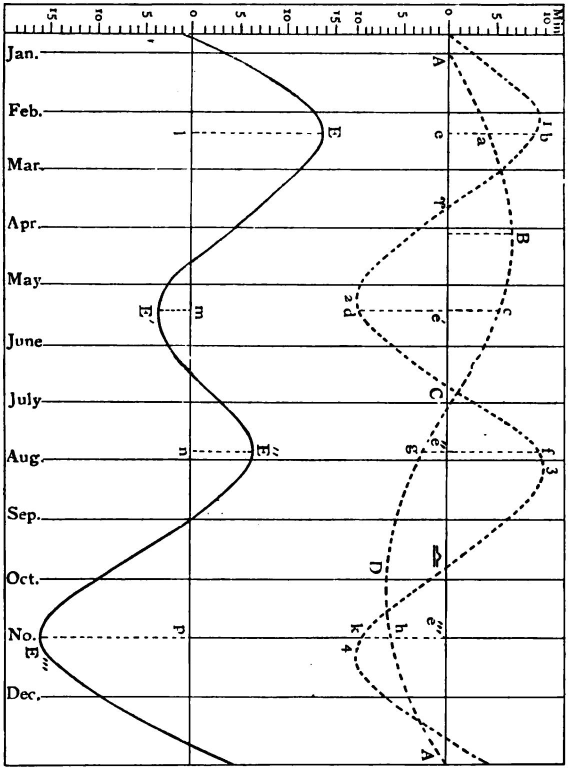

FIG. 52.—Diagram showing how the equation of time (curve E E′ E″ E‴) results from the combination of curve 1 2 3 4 representing the variation due to the obliquity of the ecliptic, and curve A B C D representing the difference between the mean and true suns

average of all its rates along the ecliptic during a year were taken; so that we get something like this (see Fig. 52).

Above and below the datum line, which is marked zero, we have 5, 10, and 15, which represent the difference in minutes at which the southings of our real and fictitious suns really take place on days in different parts of the year. First of all we have the curve 1 2 3 4, which shows the variation which would take place provided we only had to deal with the obliquity of the ecliptic. Where that curve crosses the horizontal line, we get at those moments (if we disregard the elliptic motion) the same time shown by the mean sun as we should get if the true sun had been taken; it will be seen that this occurs four times a year—on March 20, June 21, September 23, and December 22. Then there is another curve, A B C D, which represents another relation between the mean sun and the true sun. Providing that the two planes were coincident, and that the movement of the earth under these conditions were exactly the same as under the present conditions, namely, that she moved in an ellipse and that the radius vector swept over equal areas in equal times, then we should have the true and mean suns coincident on December 31 and July 1 only. Then the algebraic sum of these two curves, 1 2 3 4 and A B C D, is taken, and we get as a result the lower curve E E′ E″ E‴, which is a compound of the two other curves. It will be seen that at e, where we get the curve A B C D, giving us e a, a difference of nearly five minutes, and the curve 1 2 3 4 giving us e b, a difference of about nine minutes in the same direction, we have a difference of over fourteen minutes between the motions of the real and mean suns, represented in the lower curve by E l. Early in the month of February we have a difference of very nearly fifteen minutes between the two suns, and it is at this time of the year of course that the sun-dial is most in error. At other points where the effect of curve 1 2 3 4 is to cause a great difference, the effect of curve A B C D is to minimise that difference, so in the compound curve $E\,E'\,E''\,E'''$ the difference is very slight, and becomes nothing four times in the year. About the middle of June we get them together, then towards the end of July we get another separation $E''\,n$, the difference between $e''\,f$ and $e''\,g$, and about November 1 we come to another difference $E'''\,p$, the sum of $e'''\,h$ and $e'''\,k$, even greater than that in February. In this way a correction has been introduced, which is known as the "equation of time," and this added to the motion of the true sun, or added to that of our imaginary sun, brings them together, and by this means the mean sun is kept as nearly as possible to the average position of the true sun throughout the year.

Mean time.

It has already been said that it is imperative, if we are to gain any advantage from it, that real sun-time and apparent sun-time should never be widely separated, because if so we might have contented ourselves simply with sidereal time, which would have at least the advantage of being constant, so that it is most necessary if any benefit is to be derived from this mean sun of ours that it should not differ very much from the true sun. The longitude of our mean sun is therefore made equal to the mean longitude of the true sun. This having been premised, the terms "mean time" and "mean noon" will now be clear without any explanation. "Greenwich mean time" of course means time referred to the meridian of Greenwich.

We thus finally discard our sidereal time for the ordinary purposes of life, and replace it by mean solar time so arranged that the maximum departure of this from true solar time shall be the least possible; as a matter of fact, as we have seen, the greatest variation is fifteen minutes in the month of February and fifteen minutes at the beginning of November. We have seen that the sidereal day is shorter than a solar day, and that consequently the hours, minutes, and seconds which make up the sidereal day must be shorter than those which form the solar day. The relation between the seconds of solar and sidereal time may thus be shown.

One sidereal second = ·9973 of a mean-time second.
One mean-time second = 1·0027 of a sidereal second.

Variation in the length of the day.

We have now got the results of the earth's revolution combined with its rotation, so far as day and night, considered in their more general aspects, are concerned; but we have not done with day and night yet. When we were considering the question of the inclination of the earth's axis, we went so far as to say that it was inclined 66½° to the plane of the ecliptic, and that it always remained practically parallel to itself. Now suppose we arrange four globes in a circle, to represent the earth in different parts of its orbit, and we have in the centre an electric lamp to represent the sun. Then, if the earth's axis is thus inclined to its path round the sun, and always remains parallel to itself, it will be seen that at one position the north pole will be all in the light of the electric lamp (which represents the sun) during the entire revolution of the earth on its axis. At the point opposite this the reverse happens, for during the entire rotation of the earth the north pole will be in the dark. At the two remaining points the pole will be just on the boundary of light and darkness. We need not consider the case of the south pole; there exactly the reverse will happen to what occurs at the north pole—when the north pole is always in the light, the south pole will be always in the dark, and *vice versâ*, as may be seen by looking at the globes. Now it should be clear that the fact of the earth's axis being inclined to its path causes different lengths of day and night throughout the year. It is simply that, and nothing else. At the poles, which, as we have seen, are sometimes entirely in the light and sometimes altogether in the dark, there will be six months of this light and six months of darkness. At the equator it will be readily understood the days and nights will be of twelve hours' duration at whatever part of her orbit the earth may be. If you take those positions of the earth where the boundary of light and darkness passes through both the poles, it is perfectly clear that the days and nights are of equal length all over the world, and a line drawn from those points through the sun is therefore called the "line of equinoxes." These points are respectively at the ascending and descending nodes of the orbit. The two other points where the north pole is most in the light or in the dark during the whole of a rotation are known as the solstices, because it is at these times that the sun for some days appears to attain the same height at noon.

The seasons.

To sum up, then, it will be seen that the earth's rotation and the earth's revolution, in conjunction with the important fact of the non-coincidence of the planes in which they take place, give us not only our days and our nights, but cause the lengths of them in different latitudes to vary throughout the year. We have in this inclination of these planes to each other, too, the cause of the seasons, because when the northern hemisphere of the earth has been for a long time in that position with the sun longest above the horizon, the temperature will be very different from what it is when the earth is in the other position. In the former position we have summer in the northern hemisphere, in the latter winter. The conditions of life at two such points in the orbit will be vastly different. At the equator, where the days and nights are always of equal length, the course of nature will be very uniform. As the equator is receded from and the poles are approached, this uniformity begins to disappear until, as has been said, at the pole six months of perpetual daylight alternate with six months when there is no sun.

Precession and nutation.

But even now when we have got our day and our ordinary year, with its seasons, we have not got all.

It must next be pointed out that, whilst the axis of the earth may be said to remain practically parallel to itself during the earth's revolution round the sun, yet it does not absolutely remain so.

As a result of this and of the earth's movement round the sun, we get a very important outcome. When the true places of stars, corrected for refraction and aberration, are examined at different times, it is found that the co-ordinates are slowly but continually changing. These variations may be due to two causes: the stars themselves must move, or else the plane and point from which the measurements are made must be changing in position with respect to them. Observations show that the change in question is common to all stars, and it follows from this that it is our datum plane and point which move. Proper motions would be special to certain stars.

The actual change is an increase of $50''\cdot2$ per annum in the longitudes of all stars, the latitude remaining very nearly constant. The inference to be drawn from these facts is that the plane of the ecliptic is practically constant, while the first point of Aries—the starting-point of celestial longitude—is slowly moving backwards along the ecliptic, this retrograde motion being accompanied by a change in the direction of the plane of the equator.

We may now proceed to consider the physical cause of the gradually increasing longitudes of stars.

Although the consideration of the dimensions of the earth has scarcely come within our subject, yet the earth's rotation may be used to bring in the dimensions of the body on which we dwell in just the same way as the velocity of light was used to refer to the dimensions of its orbit.

We need not, however, consider the question in detail, but we may state that the earth is a globe of something like 8000 miles in diameter, the equatorial diameter being longer than the diameter from pole to pole by some twenty-six miles, so that we have, as it were, round the equator a ring of matter some thirteen miles thick and eight thousand in diameter. If the earth were truly spherical, the gravitational attraction of an external body upon it would have no tendency to change the direction of its axis, and therefore the plane of its rotation and the positions of the equinoxes would be constant. Now this ring of matter, this equatorial protuberance, is at times presented to the sun at an angle to the line joining the centres of the sun and earth, as shown in Fig. 53, and the sun's attraction upon it can be resolved into two forces, one parallel to the line joining the centres of the sun and earth, and the other at right angles to this direction; and if we consider what will be the effect of this latter force upon such a ring, we can easily understand that it will result in an alteration of its inclination. The same thing happens with regard to the moon's attraction.

A word about the sun's part of the attraction first. The mean attraction of the sun upon the ring is balanced by the centrifugal force of its revolution in its orbit round the sun. The attraction upon the portion at A will be greater than the mean attraction at C, because A is nearest to the sun, and hence there will be a force tending to draw A towards the sun. Similarly, the portion at B, being further removed, is subject to an attraction less than the mean, and there is consequently a surplus force tending to move B away from the sun. The resultant effect of the two forces is not to move the ring bodily towards or away from the sun, but to turn it about the centre C and to tend to bring it into the plane of the ecliptic. If the ring were once in the ecliptic, it would remain there, but this is prevented by the rotation of the earth on its axis,

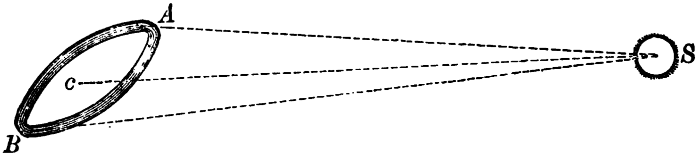

FIG. 53.—The attraction of the sun on the earth's equatorial protuberance.

the ring, like the fly-wheel of an engine, resisting a sudden change in the plane of its motion.

The result is a slow revolution of the earth's axis and a change in the plane of its equator, and consequently of the positions of the equinoxes.

When the sun is in the plane of the equator, in March and September, the differential attraction on the two sides of the protuberance has no tendency to turn it about an axis. The maximum effect is of course produced when the equatorial protuberance is most inclined to the sun, in June and December. The varying distance of the sun from the earth produces an irregularity in this action.

In an experiment for showing the effect of this attraction, the ring of matter on which the sun acts may be represented by an iron ring attached to a spinning top, and the resolved portion of the sun's pull may be imitated by the attraction of a magnet held in a nearly vertical position. As the ring rotates, the attraction of the magnet draws it out of the horizontal, and the poles revolve in a circle.

This is what takes place with the earth's axis; hence it does not always remain parallel to itself. This revolution is always slowly going on, being completed in a period of about 25,000 of our years. In consequence of this motion, what happens is this: the line of equinoxes which is at right angles to the line of solstices is constantly changing its position along the earth's orbit, producing what is called the precession of the equinoxes.

We next come to the moon's attraction. The mean annual amount of precession is, as we have pointed out, $50''\cdot2$, but there is also another periodic motion of the plane of the earth's equator, which makes the precession sometimes greater and sometimes less than the mean.

Bradley suggested that this was due to the variable action of the moon in producing precession, and the researches of physical astronomers have fully proved this to be so.

The moon is more powerful than the sun in producing precession, not because its total attraction is greater, but because the differential attraction on the two sides of the equatorial protuberance is greater than in the case of the sun. If we take the sun's distance as 23,142 terrestrial radii, and its mass as 314,760 times that of the earth, the earth's action on a particle of matter at its surface being represented by 1, then $\frac{314{,}760}{23{,}141^2}$ and $\frac{314{,}760}{23{,}143^2}$ will represent the sun's attraction on a particle on the sides of the earth adjacent to it and turned away from it respectively. In the case of the moon, the mass of which is ·0123 of that of the earth, and mean distance 60 terrestrial radii, we shall have, similarly, $\frac{\cdot 0123}{59^2}$ and $\frac{\cdot 0123}{61^2}$; it is readily seen that the differential attraction, therefore, in the case of the moon is much greater than in the case of the sun. The action of the moon, like that of the sun, is subject to variation, depending upon the relative positions of the planes of rotation and revolution, and the varying distances of the earth and moon from each other.

If the sun alone were acting in producing precession, the celestial pole would describe a circle. It would also describe a circle if the moon's attraction were constant, but since the moon's orbit is inclined to the ecliptic and its nodes are also revolving, it is constantly changing its relation to the plane of the earth's equator: the result is that the pole describes a circle with a wavy circumference.

The inequality in the precession caused by the moon's attraction is called the nutation of the earth's axis.

The tropical, anomalistic, and civil years.

Just as the revolution of the earth gives us a solar day differing from the sidereal day, so the precession of the equinoxes gives us a solar year differing from the sidereal year. The sidereal year is the time between which the earth is at one point with reference to the sun and a star, and the time when it is at that same point again. This corresponds to a complete revolution of the earth round the sun, and now that we have got our mean time and know exactly how and why we have got it, we may express the sidereal year in mean time, and say that it consists of 365·625 solar days. When we consider the fact that the line of solstices, with its conjoined line of equinoxes, varies with regard to what is called the apse line, that is, the line joining the perihelion and aphelion points of the orbit, or the axis-major of the ellipse, we get another year which is called the tropical year, which, like our mean time, is the one most used, because it brings the year into relation with our seasons. The tropical year—the time which elapses between two successive passages through the vernal equinox—is shorter than the sidereal one, owing to the precession of the equinoctial points along the orbit, and consists of 365·242 mean solar days, and the difference between the lengths of this and the sidereal year will of course give the annual amount of precession which takes place.

Anomalistic year is the term applied to the period which elapses between two successive passages through the perihelion or aphelion points of the orbit; and as these points have a forward motion along the orbit, this year is longer than the sidereal one, being 365·259 mean solar days.

We may give the exact lengths of these years in days hours, minutes, and seconds, as follows:—

	Mean solar time.			
	d.	h.	m.	s.
Mean sidereal year = 360°	365	6	9	9·6
Mean tropical year = 360° − 50″·2...	365	5	48	46·0544
Mean anomalistic year = 360 + 11′...	365	6	13	49·3

The civil year consists of 365 days, so that it is about a quarter of a day shorter than the actual year. To correct this, so as to make the seasons correspond with the months, every fourth year, or *leap-year*, consists of 366 days. This addition, however, is a little too much; and, in order to make it a little more accurate, one leap-year is omitted in each century.

The Movements of the Earth are so important to us, and so interesting in themselves, that it is not possible in the space at our disposal to exhaust all that may be said about them or learned from them. I trust however that I have left no point of the first importance untouched.

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